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# SEALING OF LARGE-DIAMETER BOREHOLES FOR LL & IL REACTOR WASTE DISPOSAL

*Report No 88-105-K*

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*ABSTRACT*

The objectives of this study were: (1) to evaluate the performance of the instrumentation installed in the backfilled boreholes which were augered into glacial till at the BNPD waste management site in 1984, and (2) to examine some of the potential problems associated with the use of concrete material in backfilling a large-diameter borehole in clay soils. The report summarizes the work done and the results obtained in several areas: (1) evaluation of field instrumentation data obtained at the BNPD site, (2) numerical analysis of the heat dissipation from a large concrete plug (backfill) into the surrounding soil, (3) radionuclide migration along a gap at the clay/concrete interface and (4) laboratory hydraulic conductivity tests on clay samples with cement grout cores.



| job | file | date | report no. |
|---|---|---|---|
| 43-335-430 | 843.2 | May 16, 1988 | 88-105-K |

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# SEALING OF LARGE-DIAMETER BOREHOLES FOR LL & IL REACTOR WASTE DISPOSAL

## 1. INTRODUCTION

The Soil Sciences Section staff have been involved since 1984 in a study to evaluate the suitability of large-diameter augered boreholes for the disposal of Low-Level and Intermediate-Level Wastes (LLW & ILW). The disposal concept consists of augering boreholes of 1.5 to 3.0 m in diameter to a desired depth, placing the waste containers at the base of the hole and backfilling the space around and above the containers with a material of low permeability. A concrete slab and a compacted clay cover placed over the backfilled borehole would provide protection and proper surface drainage.

A field study was initiated in the fall of 1984 at the Bruce Nuclear Power Development (BNDP) waste management site. This field study consisted of augering three large-diameter (1 to 2 m) boreholes to depths of 5.5 to 7.5 m, placing steel drums at the bottom and backfilling. Further details of this study, including monitoring results for the first 8 months were provided by Radhakrishna (1985)/1/.

The objective of the present study was twofold: 1) to assess further the performance of instrumentation and backfill materials placed in the large-diameter boreholes augered into glacial till at the BNPD site in 1984, and 2) to examine the viability of the backfilled borehole concept with emphasis on the flow path at the clay/backfill interface. It is assumed in the present study that concrete is used as the backfill material in a borehole. The decision is based on the conclusion by Radhakrishna/1/ that superplasticized fly ash concrete performed well in terms of field operation and material properties.

This report summarizes the work done and the results obtained in the following categories:

(1) field instrumentation monitoring at the BNPD waste management site;

(2) numerical analysis of heat dissipation from a large concrete plug (backfill) into the surrounding soil medium;

(3) contaminant migration along a gap at the clay/concrete interface; and

(4) laboratory hydraulic conductivity testing of composite clay/grout samples.

## 2. EVALUATION OF FIELD INSTRUMENTATION RESULTS

The locations of the three large-diameter boreholes augered in 1984 at the BNPD waste management site are shown in Figure 1. Three types of backfill materials were used in the test program: 1) superplasticized fly ash concrete, 2) sand-bentonite mix, 3) excavated glacial till. The boreholes were instrumented with standpipe, pneumatic and hydraulic-type piezometers and moisture gauges. Borehole construction details and instrumentation layouts are provided in Figures 2 to 4.

From November 1984 to September 1986, only six sets of data were obtained, making detailed interpretations difficult. However, the following statements concerning instrumentation can be made:

(1) the moisture gauges still provide readings but no calibrations are available to convert these readings to moisture contents;

(2) none of the three Solinst hydraulic piezometers are operational;

(3) the pneumatic piezometer readings in the till-backfilled and sand-bentonite backfilled boreholes indicate that water levels are at or just below ground surface, which is most likely due to ponded water in the depressions produced by the settlement of the backfills;

(4) the standpipe and pneumatic piezometer readings do not correspond, even though they are located in the same position;

(5) the sensitivity of the pneumatic piezometer readings is 0.25 psi or 18 cm of water;

(6) the standpipe piezometer readings from the concrete-backfilled borehole are inconsistent and cannot be interpreted in terms of water table position (Table I);

(7) the concrete backfill piezometers are not connected to the barrel piezometers based on a short hydraulic response test (Table I).

Water level readings from a nearby University of Waterloo piezometer nest (UW-O) are listed in Table II. Based on these readings and the calculated hydraulic gradients, the water table elevation is between 189 and 190 m ASL, or 2 to 3 m below ground surface.

## 3. HEAT RISE OF CURING CONCRETE IN A LARGE-DIAMETER BOREHOLE

As a concrete mass cures, a significant amount of heat is produced due to the heat of hydration of the cement fraction. The heat of rise of the curing concrete is a function of several parameters: 1) volume, thermal conductivity, specific heat capacity and density of the concrete mass; 2) type and weight of cement per volume of concrete; 3) ambient and placing temperatures and type of boundary conditions. Akgun and Daemen (1986)/2/ reported temperature measurements within curing concrete cylinders with dimensions ranging from 108 to 197 cm in diameter and 159 to 394 cm in length. The specimens showed maximum curing temperatures ranging from 37.5°C to 95.7°C (depending on plug size and placing temperature) after 6 to 12 hours of cement hydration. Temperatures generally returned to ambient within 25 hours of placement.

The heat rise temperatures and times are associated with relatively small volumes in the previous tests. The volumes of concrete needed for sealing large-diameter boreholes for LLW and ILW are significantly larger, ie borehole diameters from 1.5 to 2.0 m and lengths from 4.0 to 7.0 m. The important question, in terms of containment, becomes whether the curing temperatures will be high enough to cause moisture migration and subsequent desiccation of the clay at the concrete/clay interface, producing a gap.

### 3.1. Finite Difference Equation for Heat Flow

In an attempt to answer the above question on a theoretical basis, a main frame computer program was obtained from the Concrete Technology Section of Civil Research. This program had been developed and used to predict the heat rise curves of concrete slabs and waiting periods necessary to minimize early age thermal cracking. This FORTRAN program named TREVOR.FOR was first modified to compile and run on a microcomputer using Microsoft's FORTRAN compiler version 3.2. At this stage, the program was renamed HEAT.FOR. The "Transient Heat Conduction" expression used in the program is a one-dimensional expression due to the large surface to thickness ratio of the concrete slabs studied. The solution is based on a finite-difference approximation technique with known initial and boundary conditions. A detailed development of the solution is provided in Tenn (1984)/3/.

For the purposes of modelling heat flow in a backfill plug, the "Transient Heat Conduction" expression was transformed into a one-dimensional radial system. The expression also allows input of different thermal conductivities to model the transition between different materials such as concrete and soil.

The governing equation for heat flow in a one-dimensional radial system was provided by Dr. A. Chan of the Mechanical Research Department:

$$\rho \, Cp \, \frac{\partial T}{\partial t} = \frac{\partial}{\partial r} \left[ k \, \frac{\partial T}{\partial r} \right] + \frac{k}{r} \, \frac{T}{r} + \dot{q} \qquad (1)$$

where, $\rho$ = density (kg/m$^3$)
Cp = specific heat capacity (J/kg °C)
T = temperature (°C)
t = time (min)
k = thermal conductivity (J/s m °C)
r = radial distance (m)
$\dot{q}$ = Q/k
Q = rate of heat generation due to cement hydration (kJ/kg min)

The left-hand boundary condition at the centre of the concrete plug was taken as adiabatic, ie. $\frac{\partial T}{\partial r} = 0$. The right-hand boundary condition located at some distance within the soil was taken as isothermal, ie. $T_{boundary} = T_{ambient}$. The initial conditions were $T(r,0) = T_{placement}$ for $0 \leq r \leq$ plug radius (R1) and $T(r,0) = T_{ambient}$ for $R1 \leq r \leq R2$ (radial distance to right-hand boundary). The heat source term in (1), $\dot{q}$, was set to zero within the soil region. The finite difference expression for (1) becomes:

$$(\rho\, Cp)_i \frac{T_i^{n+1} - T_i^n}{\Delta t} = \frac{1}{\Delta r}\left[k_{i+1/2}\ \frac{T_{i+1}^n - T_i^n}{\Delta r} - k_{i-1/2}\ \frac{T_i^n - T_{i-1}^n}{\Delta r}\right]$$

$$+ \frac{k_i}{r}\ \frac{T_{i+1}^n - T_{i-1}^n}{2\Delta r} + \dot{q}_i \qquad (2)$$

where, i = radial position of central node
n = time increment

Rearranging (2):

$$T_i^{n+1} = T_i^n + \frac{\Delta t}{(\rho\, Cp)_i}\left[k_{i+1/2}\ \frac{T_{i+1} - T_i^n}{(\Delta r)^2} - k_{i-1/2}\ \frac{T_i^n - T_{i-1}}{(\Delta r)^2}\right.$$

$$\left. + \frac{k_i}{r}\ \frac{T_{i+1}^n - T_{i-1}^n}{2\Delta r} + \frac{Q_i}{k_i}\right] \qquad (3)$$

In the new FORTRAN program PLUG.FOR, the time step for the finite difference approximation has been fixed at 15 minutes. The heat source term in this program is developed from a separate file containing theoretical heat generation data for various types of cement. This file provides heat generation data at 12 hour increments for a total of 720 hours (30 days) (Figure 5). The 15 minute time step procedure requires a linear interpolation between the given points to create a sufficiently detailed heat generation file.

### 3.2. Testing Isothermal Boundary Condition

The right-hand boundary condition was chosen to be isothermal and equal to the ambient soil temperature as this would reproduce the in-situ condition more realistically. However, the position of this boundary could unfavourably influence the heat dissipation profile by forcing it to the ambient condition. Figure 6 shows a sensitivity analysis on PLUG.FOR with increasing distances to the right-hand boundary condition. All of the simulations were produced using the following parameters:

- type 10 cement
- plug radius = 1.0 m
- concrete density = 2400 kg/m$^3$
- concrete thermal conductivity = 1.7 J/s-m °C
- concrete specific heat = 840 J/kg-°C
- weight of cement = 250 kg/m$^3$
- concrete placing temperature = 10°C
- soil density = 2100 kg/m$^3$
- soil thermal conductivity = 1.3 J/s-m °C
- soil specific heat = 960 J/kg-°C
- soil temperature = 8°C
- interval length for finite differences = 0.125 m
- soil thickness (distance to RHS) = 0.5, 1.0, 1,5, 2.0, 2.5, 3.0 m.

The thermal properties for the soil and concrete were taken from data published in Bose et al (1985)/4/. As the distance approaches D = 4.0 R where D = distance to the boundary and R = borehole radius, the change in the heat of rise at the concrete/clay interface becomes sufficiently small indicating only a minor influence of the isothermal boundary.

From Figure 6, a maximum temperature of 19.6°C is obtained on the clay side of the concrete/clay interface between 108 and 144 hours (4.5 and 6 days) after placement of the concrete plug. At 720 hours (30 days), the concrete/clay temperature is at 15.3°C or 7.3°C above ambient.

### 3.3. Temperature Profiles With Time

Figure 7 is a plot of temperature profiles with time for a right-hand isothermal boundary located at 4 x plug radius away from the plug centre. A maximum temperature of 29.4°C is attained at the centre of the concrete plug 48 hours after placement. At 720 hours this temperature has decreased to 16.3°C.

The initial placing temperature of the concrete is an important factor in determining the ultimate heat of rise within the concrete plug. The placing temperature is a function of the ambient surface conditions at mixing time. An additional simulation was performed for D = 4.0 R and a placing temperature of 25°C. The results presented in Figures 8 and 9 indicate that a maximum core temperature of 43.8°C is attained in 48 hours and that a maximum concrete/clay temperature of 26.5°C is attained in 108 hours (4.5 days). The final concrete/clay temperature is 19.5°C at 720 hours (30 days).

### 3.4. Conclusions

The ultimate temperatures at the concrete/clay interface do not appear high enough to significantly influence the moisture content and volume change of the surrounding clays. The relationship between ultimate temperatures, temperature gradients, time and moisture migration cannot be clearly established for fine-grained soils. For the sake of completeness, the thermal gradients in the clay at the concrete/clay interface are plotted versus time in Figure 10. A large-scale borehole plugging test, with temperature measurements, could be used to validate the modelling procedure and final conclusions.

## 4. RADIONUCLIDE TRANSPORT ALONG CONCRETE/CLAY INTERFACE IN LARGE-DIAMETER BOREHOLES

Heystee (1985)/5/ states that the backfilling and sealing of a disposal facility is critical to ensure that all former access routes to the subsurface be properly sealed. Improper sealing of the borehole would create a pathway for surface water and near-surface ground water to flow into the facility, greatly accelerating the saturation process and the likelihood of aqueous radionuclide release.

The most obvious pathway in the augered borehole concept is along a gap generated at the backfill/clay interface. The backfill material will be assumed to be a concrete material for the remainder of this discussion.

### 4.1. Analytical Solution for Transport Along a Fracture

The simplest and most likely mechanism by which radionuclides could migrate to the surface via a gap at the concrete/clay interface is by free-solution diffusion. However, a straight application of Fick's law of transport governed by a concentration gradient, is not applicable in the case of contaminant transport through a fracture. The role of contaminant diffusion into the adjacent matrix has been shown to be an important factor in transport through fractured media/6,7/. Tang et al (1981)/8/ developed analytical solutions for both transient and steady-state transport of contaminants along a two dimensional fracture. Their approach to simulating the transport processes in such a system was to use two coupled, one-dimensional equations, one for the fracture and one for the porous matrix. The coupling was provided by the continuity of fluxes and concentrations along the interface. Although transport along the concrete/clay interface of a backfilled borehole will be different from that in the fracture-matrix system modelled by Tang et al (1981), an application of their solution will provide a better understanding of the nature and importance of the various transport parameters involved.

Heystee/5/ states that the principle radiological hazard associated with the disposal of LLW and ILW will most likely be from the long-lived Carbon-14 in the water purification wastes. The object of concern then, is whether or not $C^{14}$ will travel to the surface by diffusion along the concrete/clay interface. Since radioactivity of $C^{14}$ decays with time, the simplified steady-state fracture transport solution provided by Tang et al (1981) can be applied to determine the ultimate length of penetration of the radionuclide.

The solution is of the form:

$$d_\delta = \frac{\ln \delta}{\upsilon - (\upsilon^2 + \psi/D)^{1/2}} \qquad (4)$$

where

| | | |
|---|---|---|
| $d_\delta$ | = | length of penetration along fracture (L) |
| $\delta$ | = | concentration ratio of interest (C/Co) |
| $\upsilon$ | = | v/2D |
| v | = | ground water velocity in fracture (L/T) |
| D | = | hydrodynamic dispersion coefficient in fracture ($L^2/T$) |
| | = | $\alpha_L$ v + D* |
| $\alpha_L$ | = | dispersivity along fracture axis (L) |
| D* | = | free water diffusion coefficient ($L^2/T$) |
| $\psi$ | = | $\frac{\lambda + \theta\,(D'\lambda)^{1/2}}{b}$ |
| $\lambda$ | = | decay constant ($T^{-1}$) |
| | = | $(\ln 2)/t_{1/2}$ |
| $t_{1/2}$ | = | half-life (T) |
| $\theta$ | = | porosity |
| D´ | = | effective diffusion coefficient in matrix ($L^2/T$) = $\tau$ D* |
| $\tau$ | = | matrix tortuosity |
| b | = | half-aperture of fracture (L) |

In the parametric analysis of equation (4), the ground water velocity in the fracture is equal to zero and the hydrodynamic dispersion coefficient reduces to the free water diffusion coefficient. The following starting values were used:

| | | |
|---|---|---|
| D* | = | $5.0 \times 10^{-6}$ $cm^2/s$ |
| $t_{1/2}$ | = | 5730 years |
| $\tau$ | = | 0.4 |
| $\theta$ | = | 0.19 |

Figure 11 is a plot of distance versus relative concentration, C/Co for various values of fracture apertures. The ultimate penetration length is defined as that corresponding to a C/Co of 0.01. Even with a fracture aperture of 1 mm (1,000 µm), the ultimate depth is only 1 metre. A fracture aperture of 1 cm (10 mm) produces an ultimate depth of 3.2 metres, as shown in Figure 12. Reducing the tortuosity to 0.1, a 1 cm aperture produces an ultimate depth of 4.5 m, as shown in Figure 13.

Tortuosity is used to reduce the free water diffusion coefficient to a value which represents molecular diffusion through a porous matrix. Since diffusion takes place only through the water phase, tortuosity should be a function of the moisture content of the porous medium. Porter et al (1960)/9/ performed laboratory chloride diffusion tests on several types of soils, concluding that there was a linear relationship between volumetric moisture content and a tortuosity factor. In a saturated medium, volumetric moisture content is equivalent to porosity. The porosity value of 0.19 used in the parametric analysis, corresponds to a

tortuosity factor of 0.1 to 0.15 according to graphs published by Porter et al(1960). The tortuosity factor decreases within the unsaturated zone and eventually reaches zero at a finite volumetric moisture content of approximately 0.10. The effect of decreasing matrix tortuosity implies that there will be more radionuclides available for diffusion in the fracture and travel distances will be much greater.

### 4.2. Analytical Solution for Transport in the Matrix

A steady-state solution for ultimate penetration distances into the matrix is also available in Tang et al (1981):

$$d_\delta = \frac{[\upsilon - (\upsilon^2 + \psi/D)^{1/2}]\, Z - \ln(\delta)}{(\lambda/D)^{1/2}} + b \qquad (5)$$

where Z = percentage of ultimate penetration distance in adjacent fracture at C/Co = 0.01

All other parameters of (5) have been previously defined. The following variables were input to the matrix equation:

| | | |
|---|---|---|
| 2b | = | 10 mm |
| $D^*$ | = | $5.0 \times 10^{-6}$ cm$^2$/s |
| $\tau$ | = | 0.1 |
| $t_{1/2}$ | = | 5730 yrs |
| v | = | 0.0 cm/s (in the fracture) |
| $\theta$ | = | 0.19 |
| $d_{0.01}$ | = | 4.47 m (ultimate penetration in fracture from Figure 13) |

Figure 14 is a plot of concentration profiles within the matrix at three different positions along the fracture length, ie 1/10 $d_{0.01}$, 1/4 $d_{0.01}$ and 1/2 $d_{0.01}$. From this plot it is evident that $C^{14}$ has diffused a substantial distance into the matrix. Starting at half the ultimate distance in the fracture (1/2 $d_{0.01}$), $C^{14}$ will reach an ultimate matrix penetration of 8 metres at steady-state. This confirms the importance of diffusive flux losses from the fracture into the surrounding matrix, especially where transport within the fracture is only by free water diffusion.

The matrix transport equation can be compared with the one-dimensional differential equation for diffusive transport with radioactive decay:

$$\frac{\partial C}{\partial t} - \frac{D}{R}\frac{\partial^2 C}{\partial x^2} + \lambda C = 0 \text{ for } 0 \le x \le \infty \qquad (6)$$

where

| | | |
|---|---|---|
| C | = | concentration of solute in solution (M/L$^3$) |
| D | = | effective diffusion coefficient = $\tau D^*$ (L$^2$/T) |
| R | = | matrix retardation coefficient |
| $\lambda$ | = | decay constant (1/T) |
| t,x | = | time and distance increments (T,L) |

At steady-state, $\frac{\partial c}{\partial t} \rightarrow 0$, $R \rightarrow 1$, therefore (6) reduces to:

$$D \frac{d^2C}{dx^2} - \lambda C = 0 \qquad (7)$$

The solution of (7) based on the boundary condition $(c,x) = (C_o,O)$ becomes:

$$C = C_o \exp \left[ -(\frac{\lambda}{d})^{1/2} x \right] \qquad (8)$$

For $C^{14}$ and $D = 5.0 \times 10^7$ cm$^2$/s, the steady-state travel distance is 16.63 m which corresponds well with the ultimate matrix penetration distance in Figure 14 at $d_{0.01} = 0.1$, ie close to the origin of the fracture with an aperture of 10 mm.

### 4.3. Conclusions

Based on the assumptions used in the transport scenario along the backfill/clay interface, the following conclusions can be made:

- Significant transport distances along the gap can only be obtained at apertures greater than 1 mm with matrix tortuosity on the order of 0.1.
- Even with low tortuosity values, diffusive transport into the matrix keeps the steady-state fracture penetration distance small. This is because fracture transport is only associated with free-solution diffusion.
- As matrix tortuosity decreases, for example in the unsaturated zone, and if radionuclides diffuse into the matrix from other sources, ultimate penetration distances in the fracture will correspondingly increase.
- Steady-state transport distances in the matrix are more significant than in the fracture.
- Due to the nature of the analytical solution, an order of magnitude change in the effective diffusion coefficient produces several orders of magnitude change in the ultimate matrix penetration distances. Therefore, accurate estimates of this coefficient are needed to provide meaningful results.

## 5. LABORATORY HYDRAULIC CONDUCTIVITY TESTS

The purpose of this laboratory investigation was to examine the degree of bonding between clay and concrete (or cement grout) with respect to water flow. To this end, several hydraulic conductivity tests were performed in the triaxial cell using cylindrical samples of clay with a mini-borehole drilled along the sample axis and filled with a cement grout.

The clay used in this study came from the area of the Nanticoke Thermal Generating Station and was sampled using 3.75 inch ID shelby tubes. Although these samples of silty clay of lacustrine origin are inherently different from the glacial till found at the BNPD field site, they were simpler to obtain and easier to prepare for laboratory testing. Since this investigation was of a preliminary nature, it was deemed unnecessary to undergo the added expense of obtaining undisturbed samples of the Bruce till.

The clay samples were extruded and waxed in the laboratory and stored in a moisture room until preparation before testing. Composite sample preparation consisted of drilling holes of various diameters through the long axis of the cylindrical clay samples. Large diameter drill bits were used to drill holes of 0.75, 1.0, 1.75 and 1.875 inches in diameter. Immediately after drilling, the mini-boreholes were filled with a cement grout. The composite samples were then resealed with wax and stored in a moisture room for a minimum of 28 days to allow curing. The grout mix properties were selected to be similar to those of the concrete backfill used in borehole #1, at the BNPD site in the 1984 study.

center; 1 n. Laboratory Standard Sand (S-7167): 18.15 kg Type 10 Laboratory Standard Cement: 5.28 kg Michigan Fly Ash (CL70139): 1.32 kg Melment L10 (Superplasticizer): 100 mL W/C + FA: 0.45

Because of the small diameters of the mini-boreholes, the coarse aggregate fraction of the original concrete mix was substituted entirely with sand in the grout mix.

### 5.1. Test Results

A test was performed on a control sample (ie no grout core) to determine an initial hydraulic conductivity for the clay. Subsequent measurement of the hydraulic conductivity of the composite samples helped determine the influence of a contact area at the backfill/clay interface on the total system permeability. Although an attempt was made to measure the hydraulic conductivity of the grout alone, limitations in the testing equipment, specifically the maximum allowable hydraulic pressure, and inaccuracy in burette measurements, prevented the acquisition of reliable data. Even when applying a hydraulic gradient of 200, practically no flow measurements could be made. For the purpose of the following discussion, it will be assumed that the hydraulic conductivity of the grout is at least 1 to 2 orders of magnitude less than that for the clay.

The measured hydraulic conductivity of the control sample (3.75") was $6.6 \times 10^{-9}$ cm/s. Assuming that the flow through the composite samples occurred primarily through the clay annulus, an effective area of flow was used in the hydraulic conductivity determinations (Table III). Theoretically, if the flow was uniquely through the clay annulus, the hydraulic conductivities of the composite samples should be similar to those of the control sample.

From the results given in Table III, the composite sample hydraulic conductivities are, in general, half an order of magnitude greater than the 3.75" diameter control (clay) sample.

Upon completing the flow test in the composite sample with a 0.75" diameter grout core, a clay core with a diameter of 1.4" was removed from the annulus and tested for hydraulic conductivity. The average hydraulic conductivity was equal to $9.2 \times 10^{-9}$ cm/s, still half an order of magnitude less than the composite sample value.

The results of Table III indicate that some additional flow is occurring through a higher permeability zone within the composite sample. Only the existance of a gap at the grout/clay interface of every mini-borehole sample tested could have produced these consistant results. There also does not seem to be any correlation between the grout core diameter and the hydraulic conductivity. The increase in interfacial circumference was not significant enough at the scale used, and therefore did not produce obvious changes in hydraulic conductivity.

### 5.2. Theoretical Considerations

Tokunaga 1988/10/ examined theoretically the laboratory permeability errors produced by flow along the sample/permeameter wall interface. He concluded that the ratio of gap flow to core flow ($Q_{gap}/Q_{core}$) is inversely dependent on the sample permeability (k). The presence of rather small gap widths when testing low permeability materials, contribute significantly to experimental errors. As for example, the presence of an annular gap of 3 μm, when testing a core with $K = 10^{-8}$ cm/s, can produce a gap flow one order of magnitude larger than the core flow.

In calculating the ratio $Q_{gap}/Q_{core}$, Tokunaga (1988) demonstrated that as the gap width approaches zero, flow in an annular gap is well approximated by flow through a parallel plate gap, which is a much simpler model to consider. The fluid flow along a planar gap bonded by a porous media of permeabilities $k_1$ and $k_2$ can be expressed as:

$$Q_{gap} = -\delta W \left[ \frac{\delta^2}{12} + \frac{(k_1 + k_{2)}}{2} \right] \frac{\rho g}{\mu} \frac{dH}{dZ} \ , [L^3/T] \qquad (9)$$

where
- $\delta$ = gap width, [L]
- $W$ = transverse width, [L]
- $k_1, k_2$ = gap boundary permeabilities, [$L^2$]
- $\rho$ = fluid density [$M/L^3$]
- $g$ = gravitational acceleration [$L/T^2$]
- $\mu$ = dynamic viscosity [M/LT]
- $dH/dZ$ = hydraulic gradient in the z-direction

To apply equation (9) to analyze the results of the composite sample hydraulic conductivity tests, the dimension W must be equated to $2\pi R$, where R equals the radius of the grout core.

Totalling the theoretical flow rates associated with the three components of the composite samples gives:

$$Q_{total} = Q_{core} + Q_{clay} + Q_{gap} \qquad (10)$$

where $Q_{total} = k_T \frac{\rho g}{\mu} \frac{dH}{dZ} \pi R_2^2$

$k_T$ = total system permeability

$R_2$ = composite sample radius

$Q_{core} = k_1 \frac{\rho g}{\mu} \frac{dH}{dZ} \pi R_1^2$

$Q_{clay} = k_2 \frac{\rho g}{\mu} \frac{dH}{dZ} \pi (R_2 - R_1 - \delta)^2$

$k_2$ = clay permeability

$k_1$ = grout permeability

The total system permeability is then equal to:

$$k_T = k_1 \frac{R_1^2}{R_2^2} + k_2 \frac{(R_2 - R_1 - \delta)^2}{R_2^2} + 2\delta \frac{R_1}{R_2^2} \left[ \frac{\delta^2}{12} + \frac{k_1 + k_2}{2} \right] \quad (10)$$

A sensitivity analysis was undertaken using equation (10) and parameter values equal to those of the laboratory tests. Figure 15 shows the effect of gap width in microns upon the total system hydraulic conductivity. Beyond a gap width of 1 μm, a two order-of-magntidue increase in width produces a five order-of-magnitude increase in total system hydraulic conductivity. As determined by the laboratory hydraulic conductivity tests, the diameter of the grout core does not seem to have a significant influence on the final hydraulic conductivity calculated.

Figure 16 shows the results of a sensitivity analysis based on changing the hydraulic conductivity of the grout core. Although K was varied from $10^{-12}$ to $10^{-9}$ cm/s, no change can be observed in the total system hydraulic conductivity. Therefore, the assumption of $K = 10^{-11}$ cm/s for the grout core was not unreasonable.

Based on Figure 15 with $K_{clay} = 6.6 \times 10^{-9}$ cm/s, $K_{grout} = 1 \times 10^{-11}$ cm/s and a composite sample radius of 4.76 cm, the effective gap widths for all composite samples were back calculated and range from 2 to 4 μm (see Table III).

### 5.3. Conclusions

Triaxial hydraulic conductivity tests on composite samples of grout and clay have provided data indicating that small gaps exist along the interface of both materials. Micron-size gaps can be detected with this method because of the significant influence they have on flow rates measured in low hydraulic conductivity soils.

Whether the presence of these hydraulic gaps within the composite samples is caused by inherent grout/clay bonding characteristics, or sample preparation and preservation techniques, cannot be pinpointed at this time due to the preliminary nature of this study. In addition, whether or not these laboratory results can be extrapolated to field scale remains unresolved.

## 6. FUTURE FIELD TESTING PROGRAM

From examining the data collected at the BNPD test site and from results of the modelling and laboratory work, the following suggestions are made for a future field testing program.

(1) The temperature regime in the concrete backfill and surrounding soil should be monitored during and after placement. Thermocouples should be placed at several locations within the backfill and temperature probes should be placed at various radial distances within the surrounding soil. Thermocouple trees should be placed within the backfill and adjacent soil to depths below frost penetration. These would be used to monitor seasonal changes in near-surface temperatures and the formation of ice lenses next to the concrete backfill.

(2) Standpipe type piezometers should be placed at several depths within the concrete backfill to monitor the saturation process. Electrical piezometers could be placed within the standpipes for continuous monitoring purposes. Psychrometers could also be used for determining unsaturated moisture contents.

(3) An injection port and electrical piezometers could be placed along the backfill/clay interface to allow periodic testing of the seal's hydraulic conductivity.

(4) Since the formation of a gap at the backfill/clay interface is of great importance, joint meters could be placed between the till and concrete backfill at several depths along the interface. The effects of temperature changes and material volume changes could be monitored in this way.

The main objective of installing the above instrumentation would be to examine the behaviour of the backfill/clay interface under field conditions.

Diffusion of contaminants from the waste drum into the surrounding concrete could also be studied at the same time by including an appropriate tracer with the simulated waste package. The instrumentation layout would take into account the possibility of concrete core removal in the future.

## ACKNOWLEDGEMENTS

The writers benefited from discussions with Mr. R.J. Heystee, Dr. H.S. Radhakrishna, Ms. H. Johnston and Mr. J. Deans. Mr. J. Jones performed the laboratory hydraulic conductivity tests on the clay samples with cement grout cores. Their assistance is gratefully acknowledged.

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TABLE I

Water Levels from Concrete Backfilled Borehole (#1)
(m.BGL)

| Standpipe | 29/11/84 | 23/03/85 | 25/04/85 | 14/06/85 | 09/10/85 | 15/9/86 | 16/9/86* |
|---|---|---|---|---|---|---|---|
| #1 | 3.71 | 3.70 | 3.66 | 3.65 | 3.69 | 3.61 | 3.59 |
| #2 | 5.19 | 2.65 | 2.45 | 2.79 | 3.11 | 3.10 | 3.12 |
| #3 | 6.86 | 5.80 | 5.51 | 5.22 | 4.74 | 4.37 | 4.32 |
| #4 | 6.35 | 6.35 | 6.34 | 6.34 | 5.15 | 4.75 | 6.17 |
| #5 | 7.27 | 6.72 | 6.48 | 6.22 | 4.96 | 4.72 | 6.10 |

*Pumped piezometer #5 (barrel) down to 6.68 m.BGL.
Readings taken 15 hours after pumping.

TABLE II

Water Levels in University of Waterloo Nest (Sept 15/86)

| Piezometer | Intake Elevations (m.ASL) | Water Levels (m.ASL) |
|---|---|---|
| OW-10 | 188.8 | 189.85 |
| OW-26 | 184.07 | 186.78 |
| OW-37 | 180.87 | 185.47 |
| OW-53 | 175.85 | 183.06 |

Ground Elevation = 192.0 m.ASL.

N.B.: m.BGL = metres below ground level
m.ASL = metres above sea level

TABLE III

Hydraulic Conductivities of Control and Composite Samples

CONTROL SAMPLES: (Clay Only)

| | | |
|---|---|---|
| Sample Diameter: | 3.75" (9.52 cm) | 1.4" (3.56 cm) |
| Sample Area: | 71.26 $cm^2$ | 10.28 $cm^2$ |
| Hydraulic Gradient: | 40.7 | 37.1 |
| Average Flow Rate (cc/min) | $1.16 \times 10^{-3}$ | $2.0 \times 10^{4}$ |
| Average Hydraulic Conductivity | $6.6 \times 10^{-9}$ cm/s | $8.6 \times 10^{-9}$ cm/s |

COMPOSITE SAMPLES

| | | | | |
|---|---|---|---|---|
| Sample Diameter: | 9.52 cm | 9.52 cm | 9.52 cm | 9.52 cm |
| Grout Core Diameter: | 0.75" (1.9 cm) | 1.0" (2.54 cm) | 1.75" (4.44 cm) | 1.875" (4.76 cm) |
| Effective Area of Flow Clay Only: | 68.62 $cm^2$ | 67.3 $cm^2$ | 56.23 $cm^2$ | 54.25 $cm^2$ |
| Hydraulic Gradient: | 16.9 | 14.6 | 15.0 | 14.7 |
| Average Flow Rate (cc/min): | $3.1 \times 10^{-3}$ | $2.8 \times 10^{-3}$ | $2.4 \times 10^{-3}$ | $1.5 \times 10^{-3}$ |
| Effective Hydraulic Conductivity (cm/s): | $4.45 \times 10^{-8}$ | $4.75 \times 10^{-8}$ | $4.74 \times 10^{-8}$ | $3.1 \times 10^{-8}$ |
| Total Hydraulic Conductivity (cm/s): (Total Sample Area) | $4.3 \times 10^{-8}$ | $4.5 \times 10^{-8}$ | $3.7 \times 10^{-8}$ | $2.4 \times 10^{-8}$ |
| Back Calculated Effective Gap Widths (μm) | 4 | 3.5 | 3 | 2 |

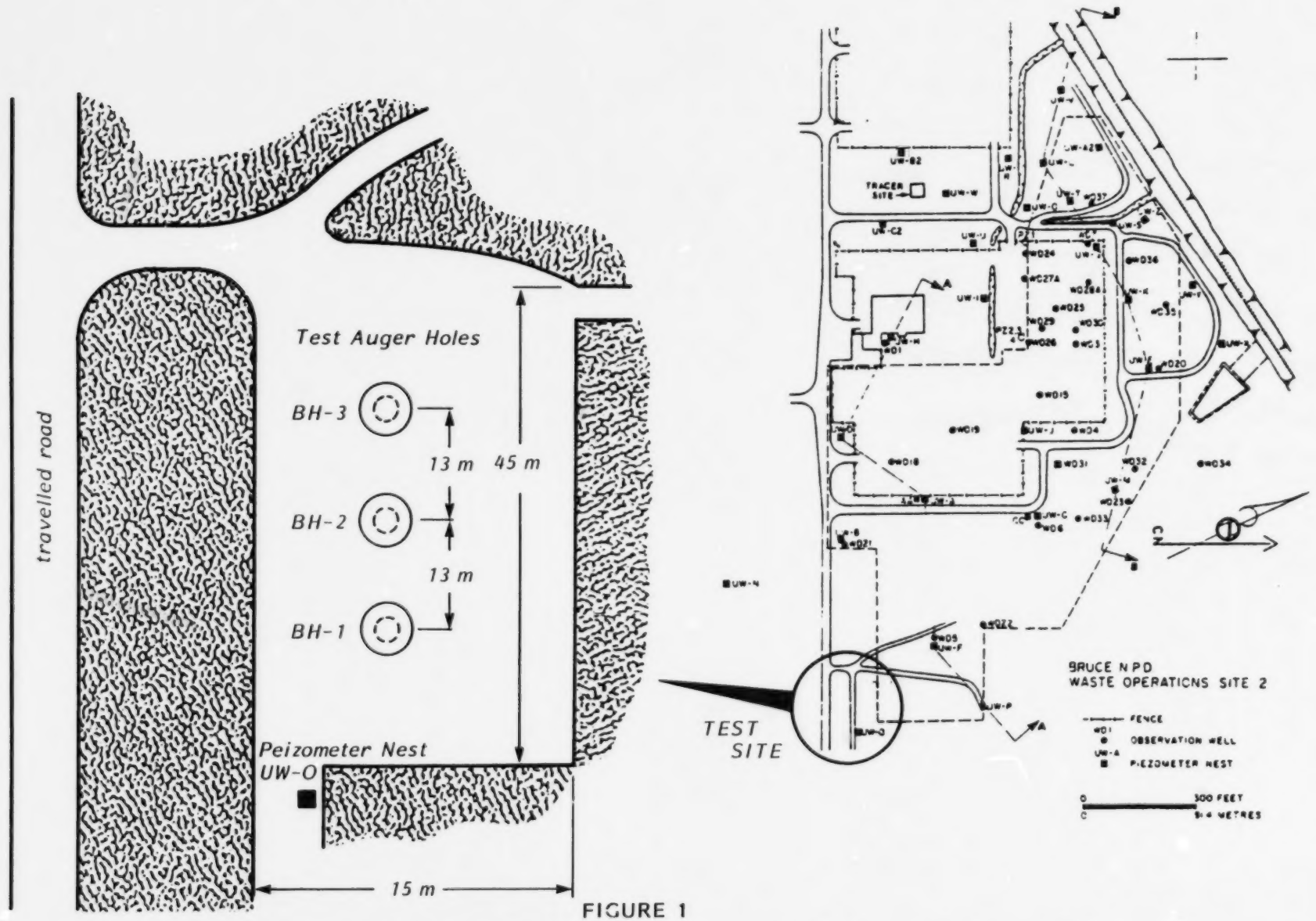


FIGURE 1

PLAN OF BNPD RADIOACTIVE WASTE OPERATIONS SITE 2 AND LOCATION OF ILW - TEST SITE /1/



167366 RD
88-105

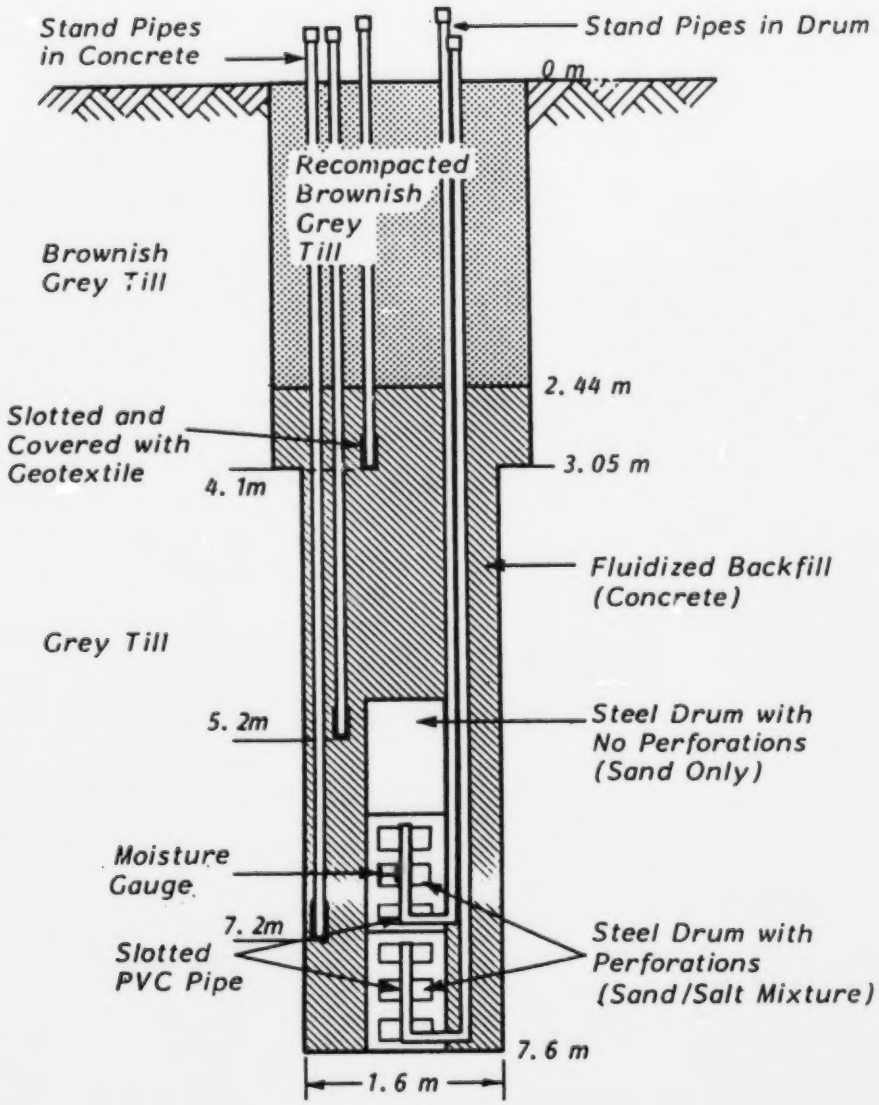


FIGURE 2

CROSS SECTION OF TEST HOLE 1
WITH SUPER PLASTICIZED CONCRETE /1/

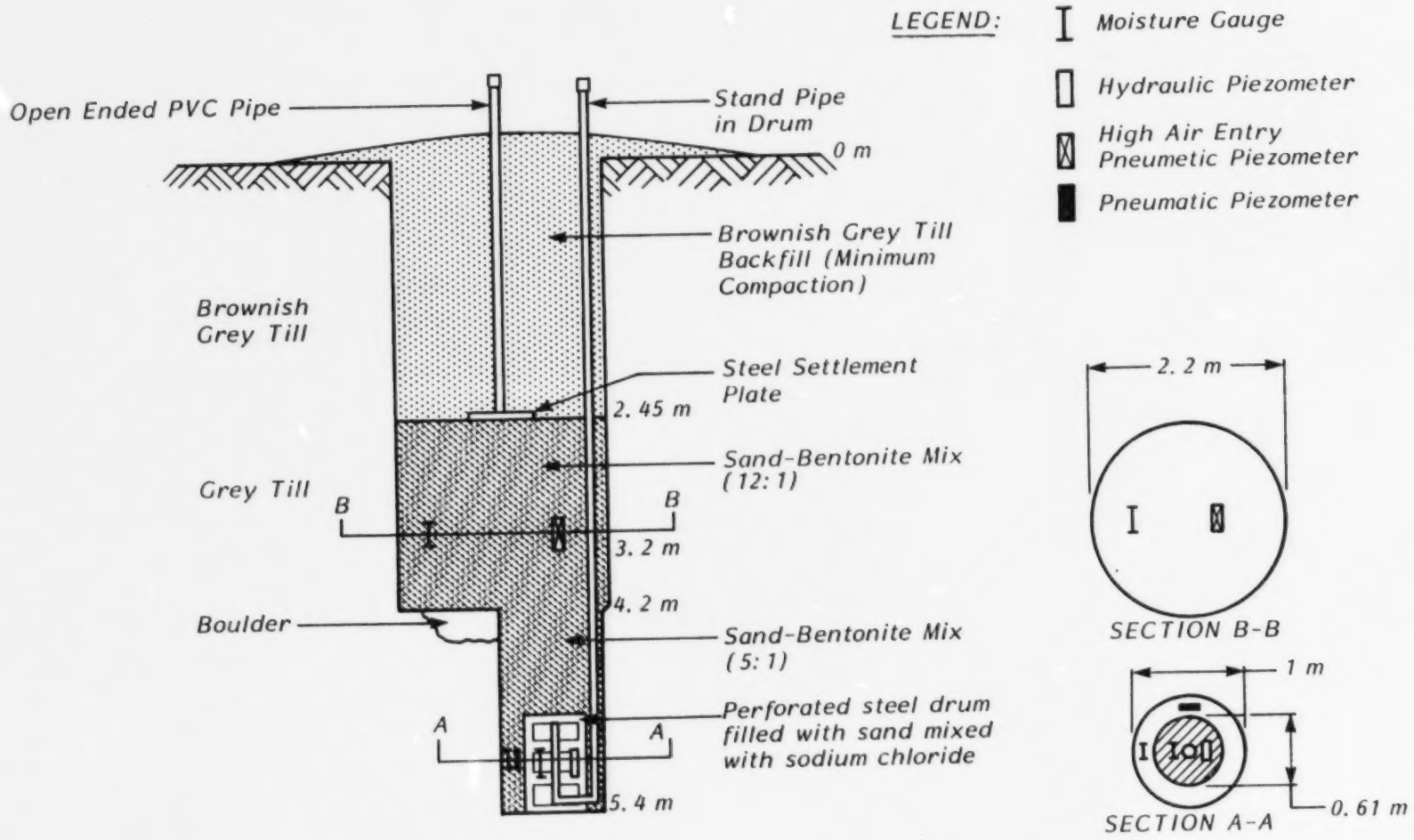


FIGURE 3

CROSS SECTION OF BOREHOLE 2
BACKFILLED WITH SAND-BENTONITE MIX /1/



88-105 167363 RD

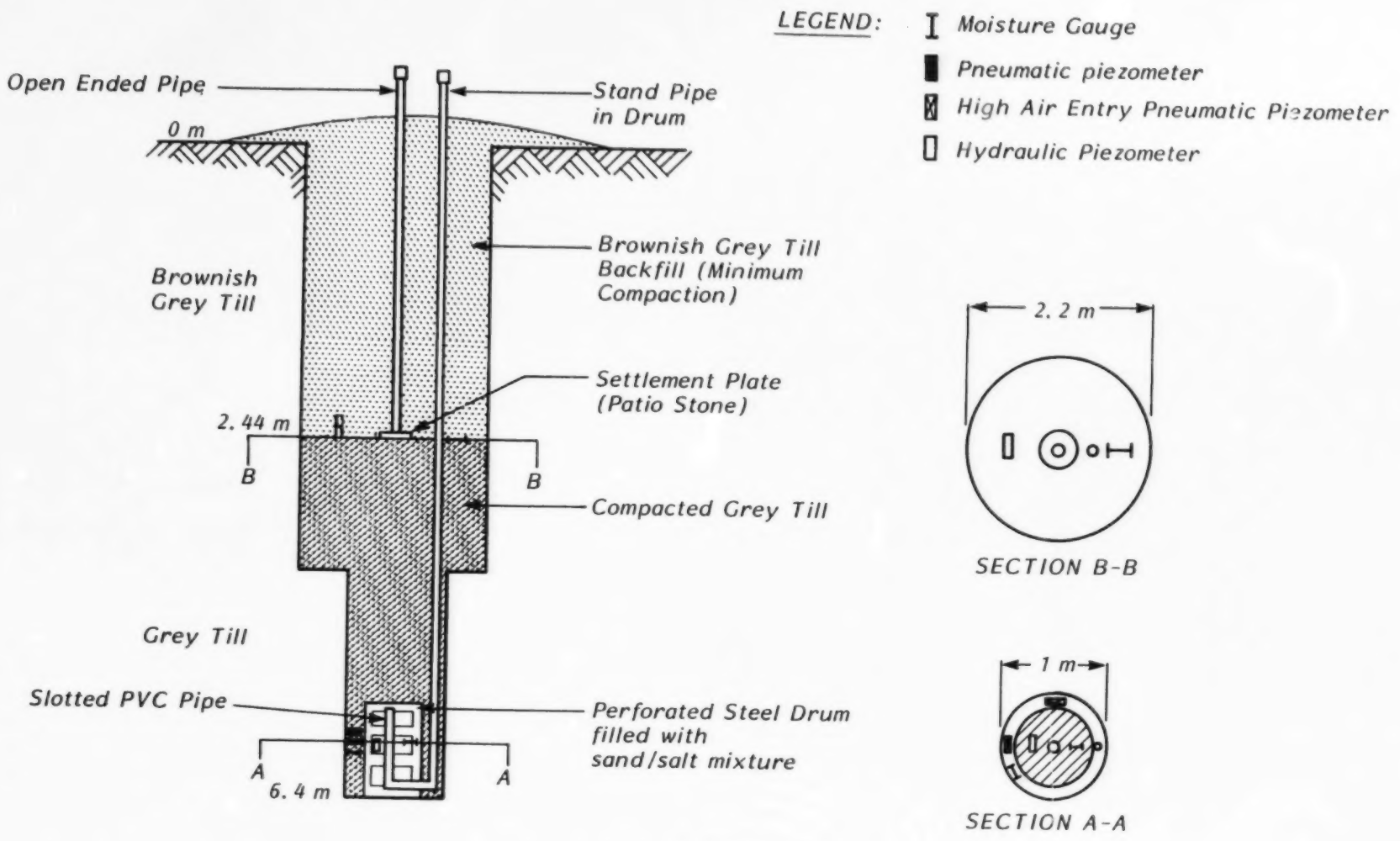


FIGURE 4

CROSS SECTION OF TEST HOLE 3
BACKFILLED WITH COMPACTED GREY TILL /1/



167364 RD
88-105

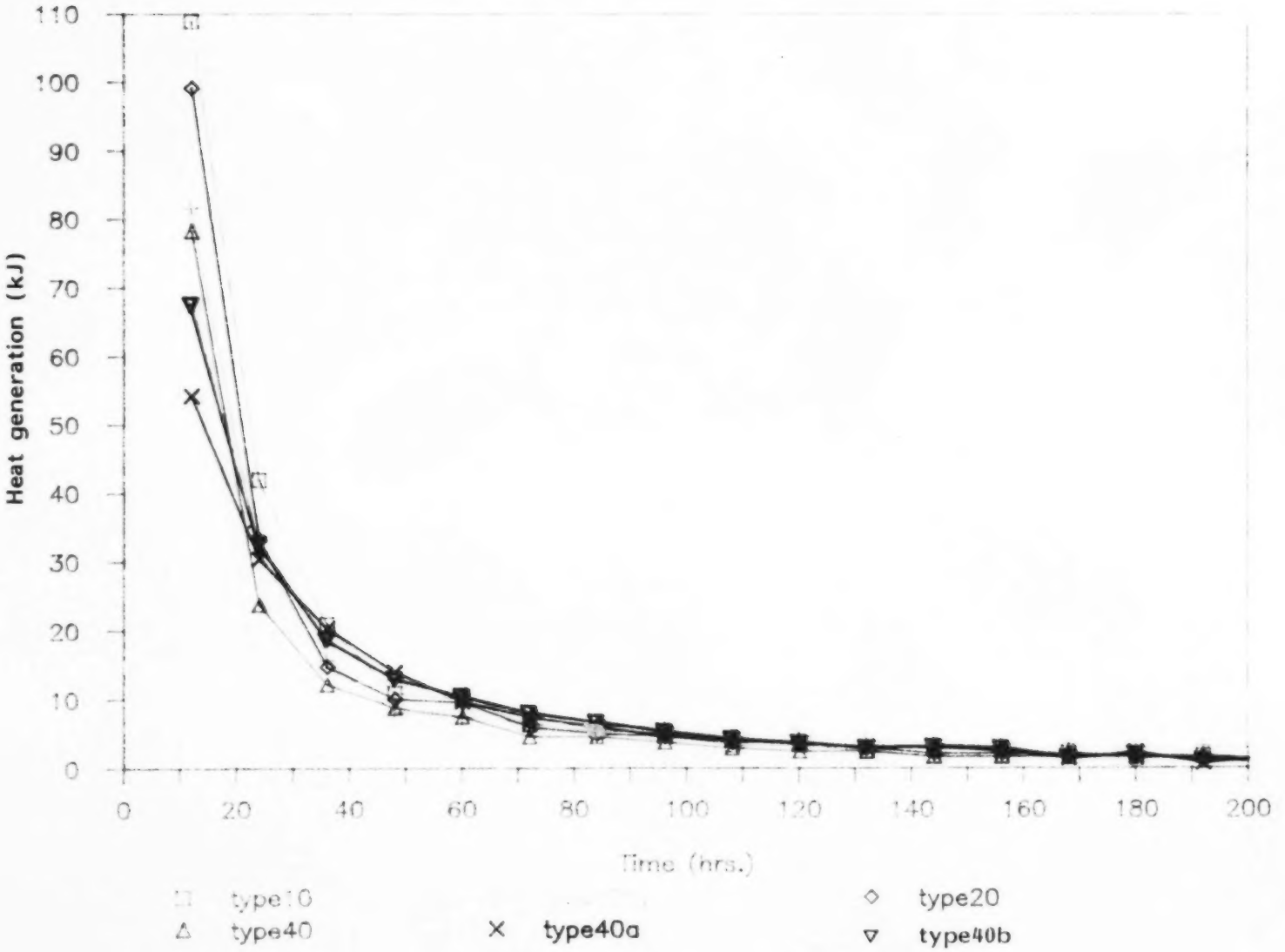


FIGURE 5
THEORETICAL HEAT OF HYDRATION

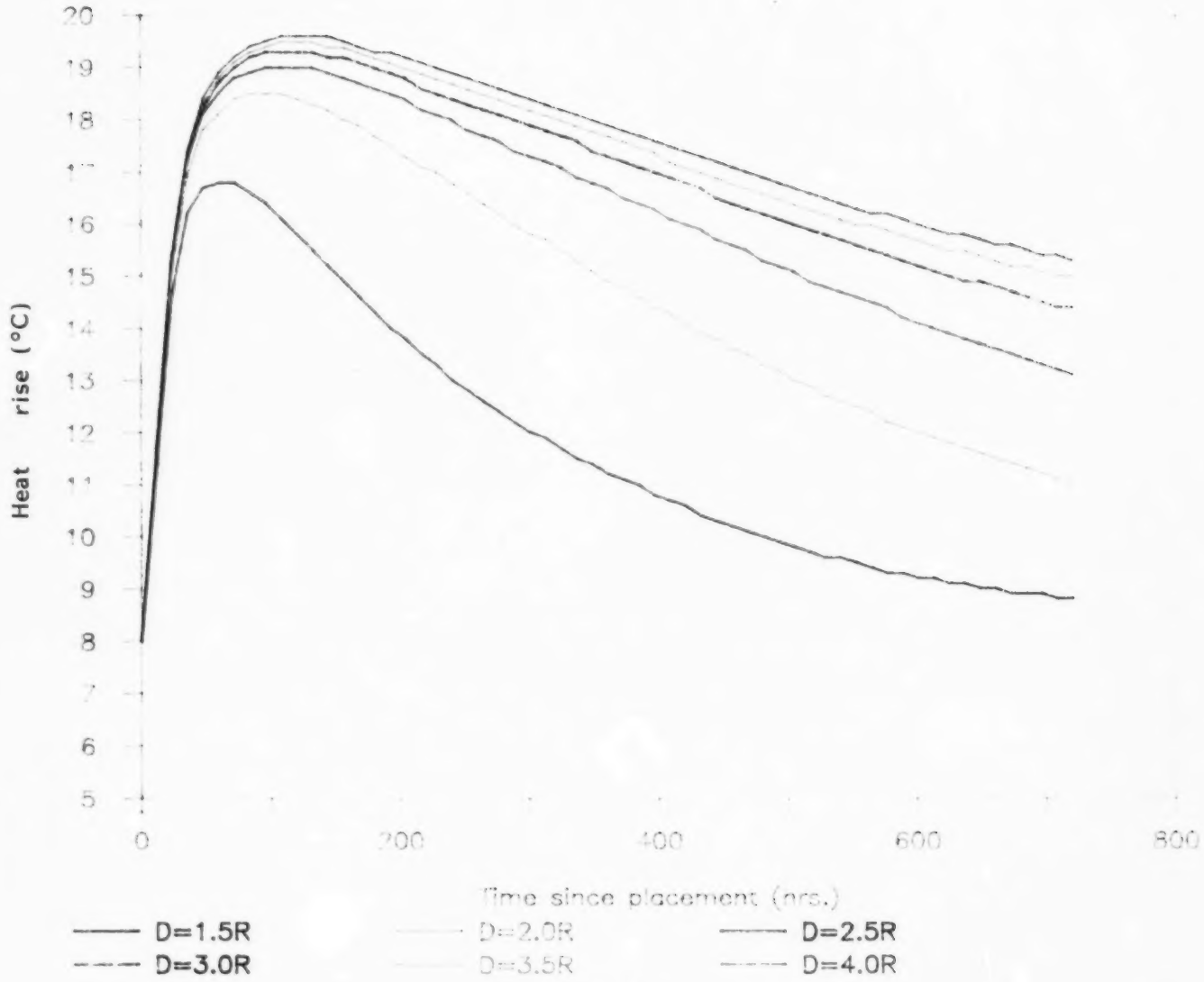


FIGURE 6

LARGE-DIAMETER CONCRETE PLUG IN CLAY

Heat rise at concrete/clay interface
D = Distance from Centre of Plug
R = Plug Radius

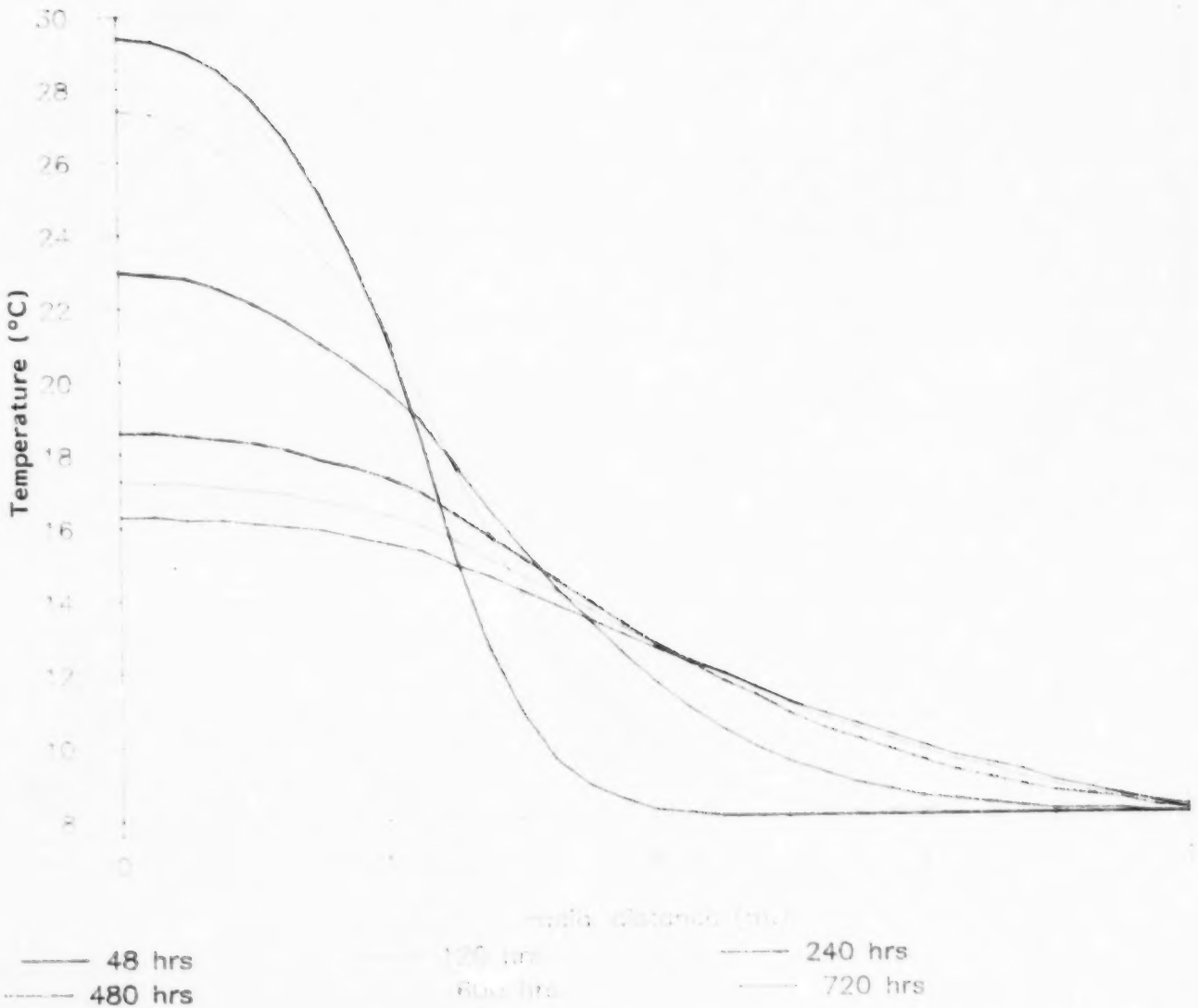


FIGURE 7

LARGE-DIAMETER CONCRETE PLUG IN CLAY

Temperature profile with time D=4.0R; Tp=10°C



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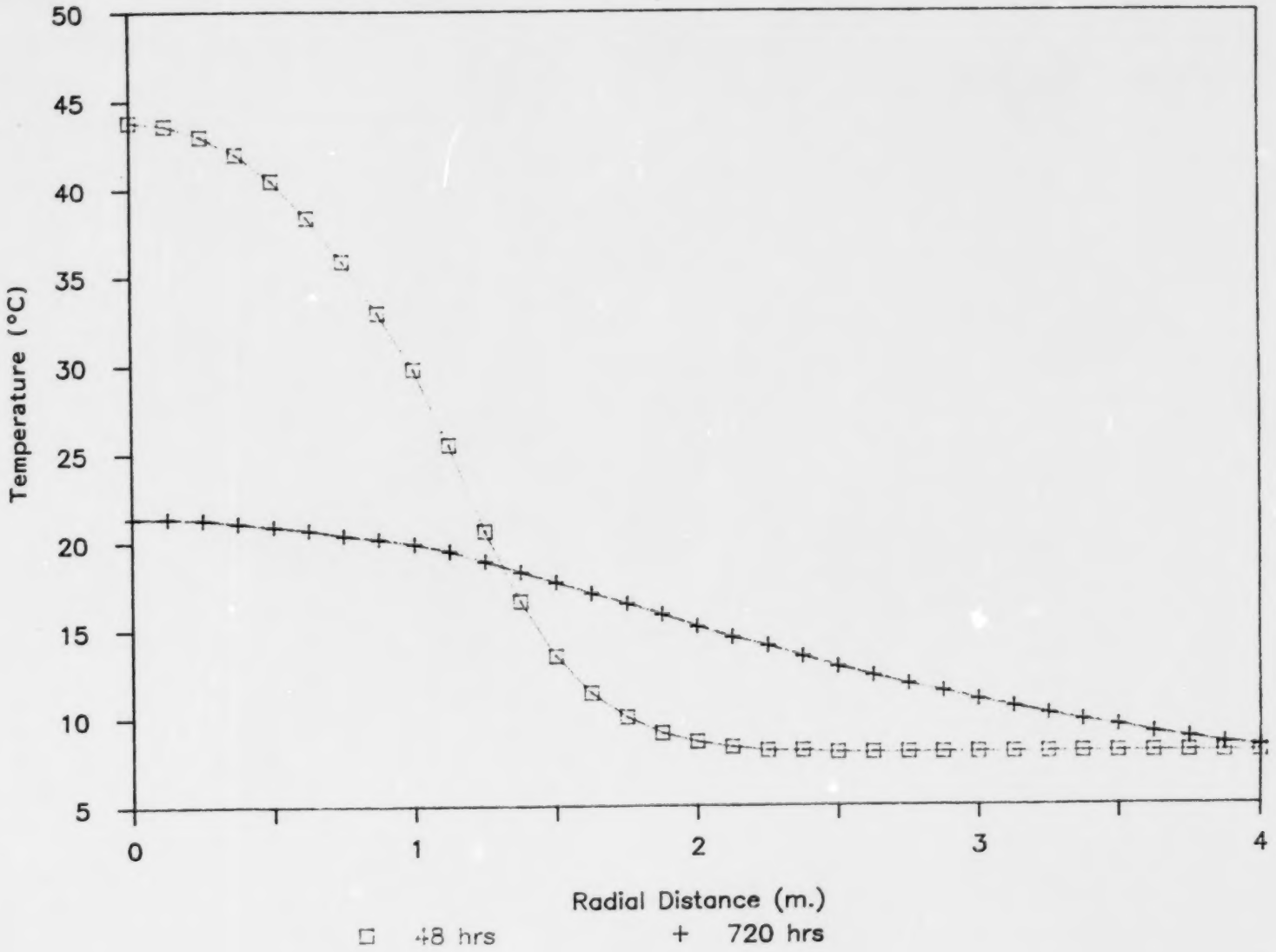


FIGURE 8
LARGE-DIAMETER CONCRETE PLUG IN CLAY
Temperature profile; D=4R; Tp=25°C

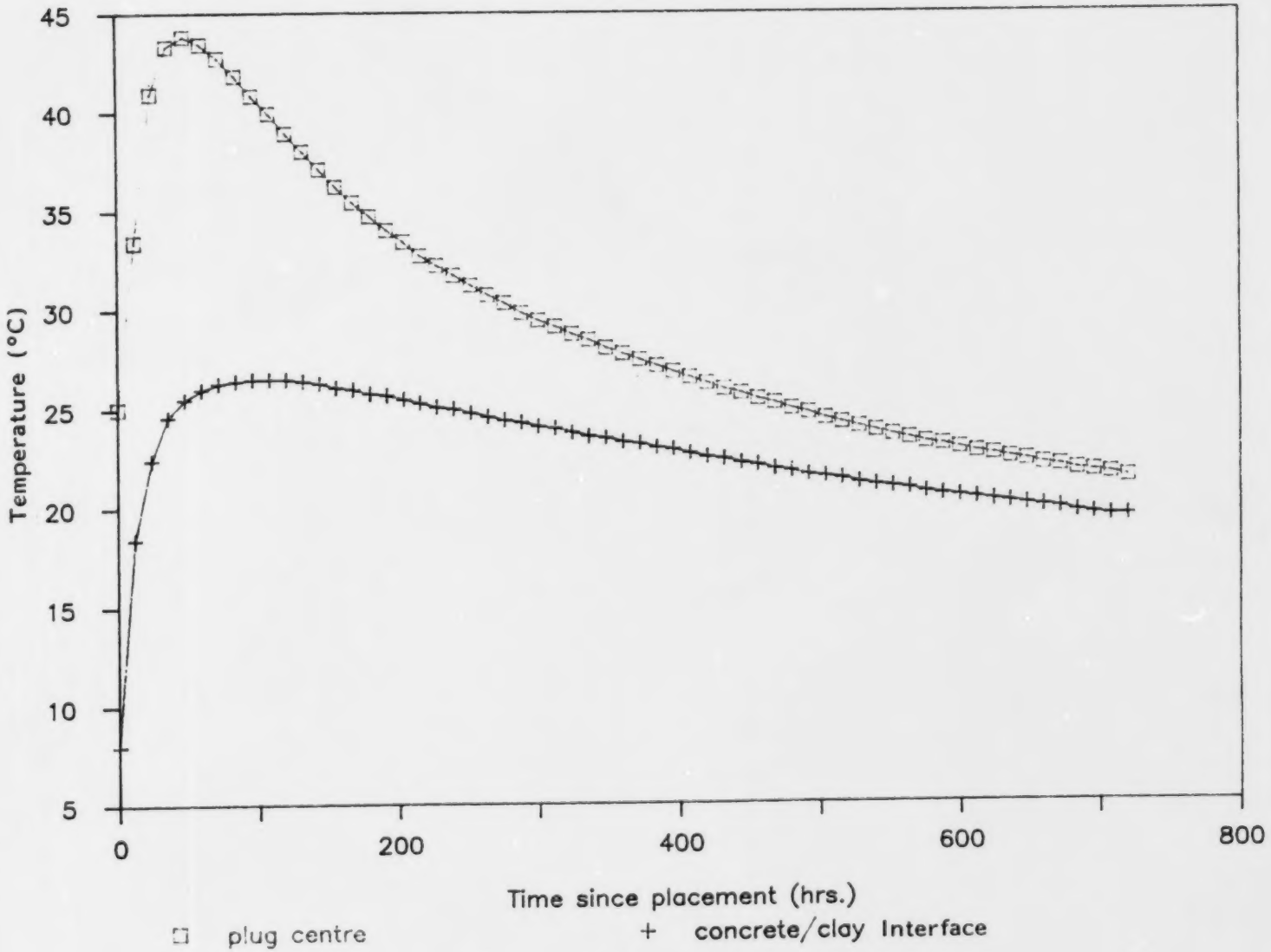


FIGURE 9
LARGE-DIAMETER CONCRETE PLUG IN CLAY
Heat rise; Tp=25°C



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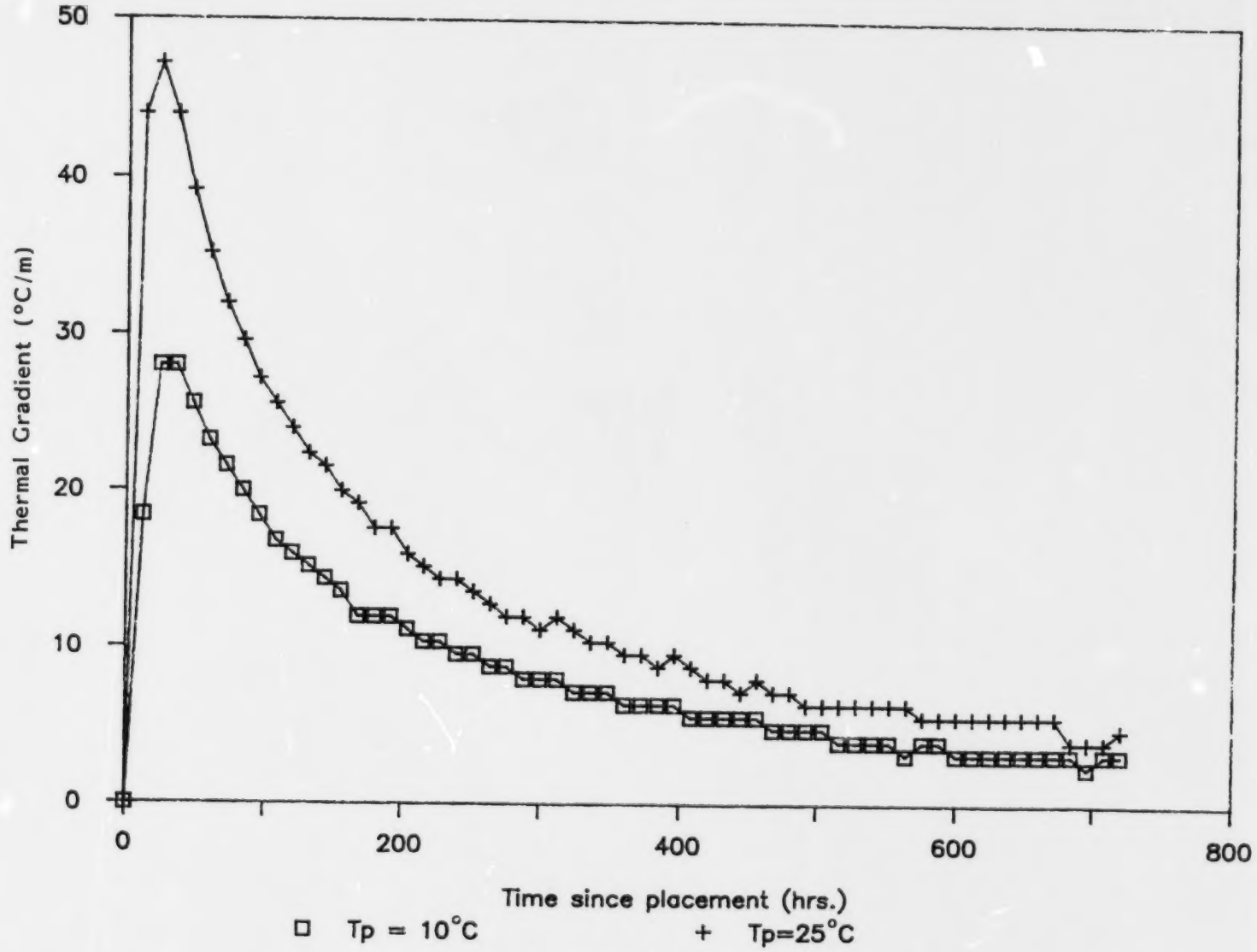


FIGURE 10

LARGE-DIAMETER CONCRETE PLUG IN CLAY

Thermal gradients in clay at interface

Tp = Placement Temperature



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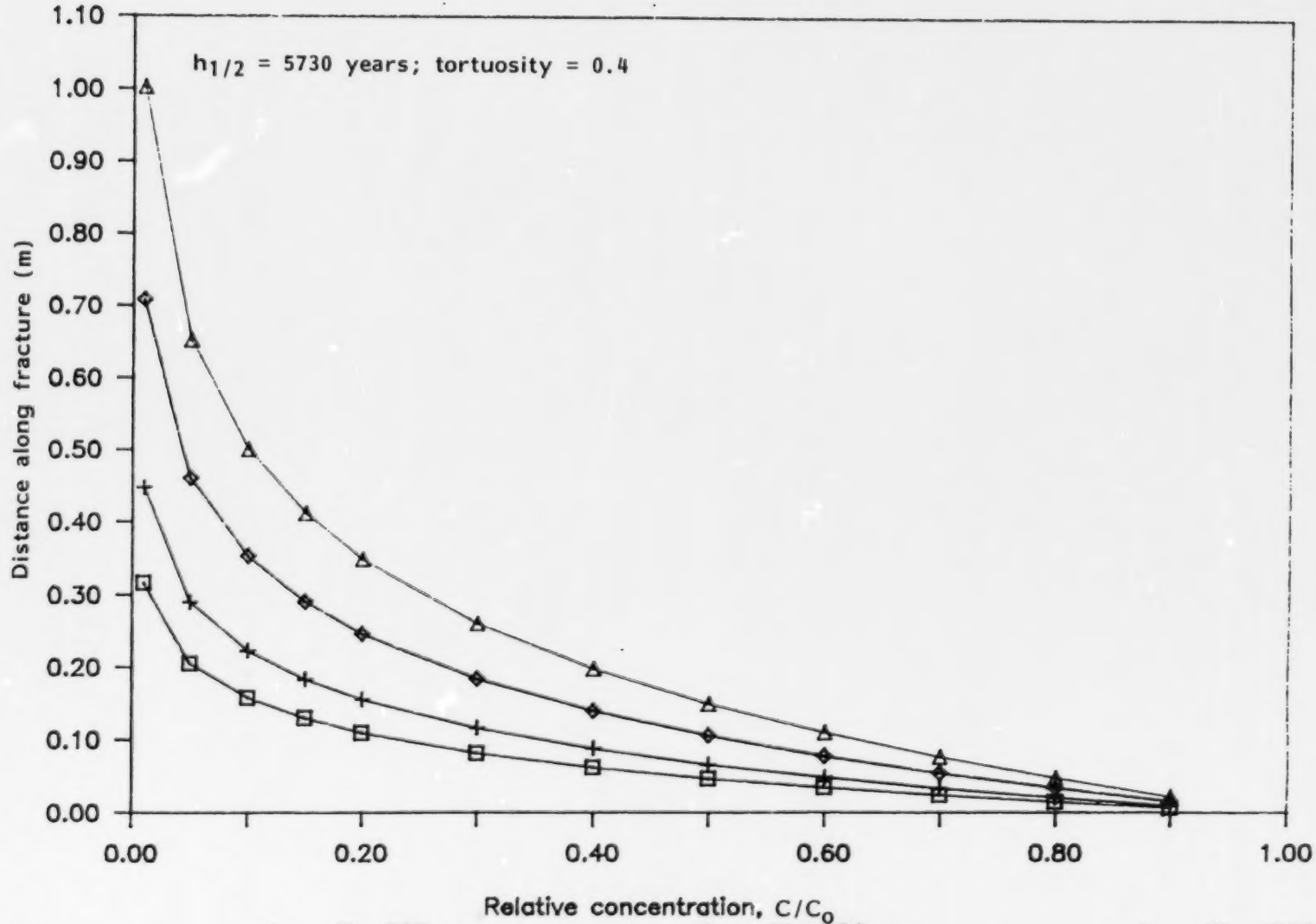


FIGURE 11
STEADY STATE CONCENTRATION PROFILE
Species: $C^{14}$: $D^*$=5.0E-06 $cm^2/s$

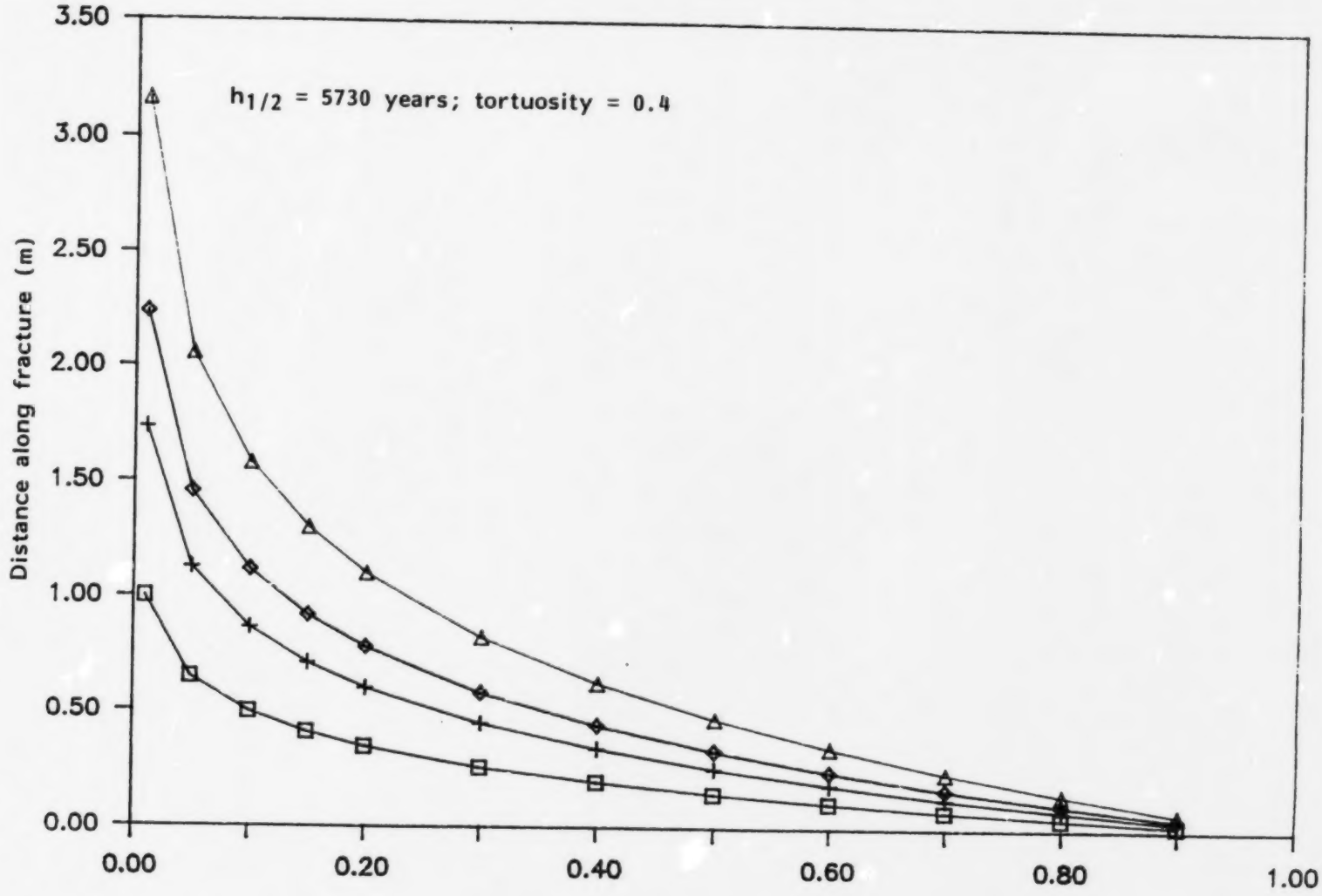


FIGURE 12

STEADY STATE CONCENTRATION PROFILES

Species: $C^{14}$: D*=5.0E-06 $cm^2/_s$

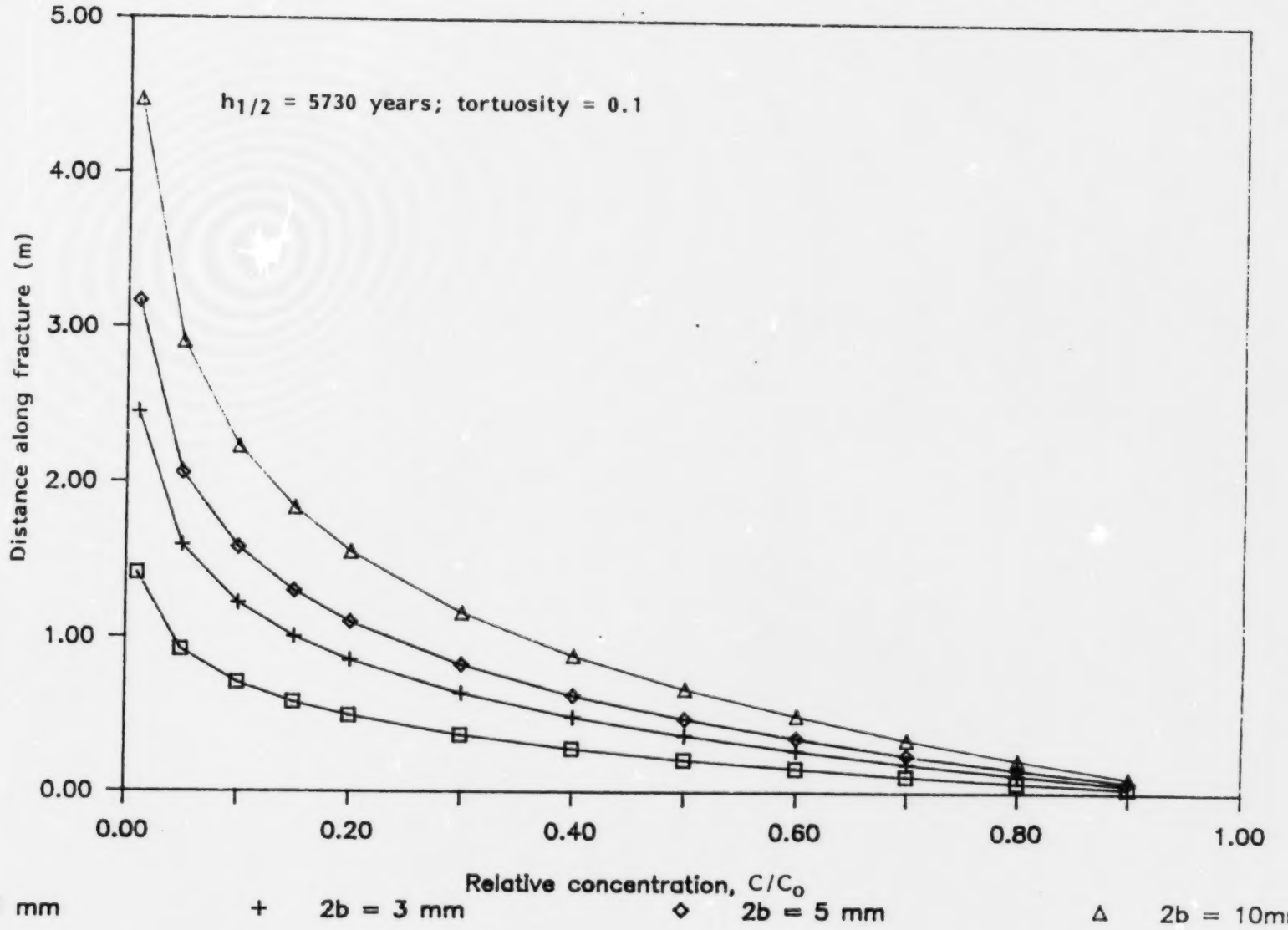


FIGURE 13

STEADY STATE CONCENTRATION PROFILES

Species: $C^{14}$: $D^*$=5.0E-06 $cm^2/s$

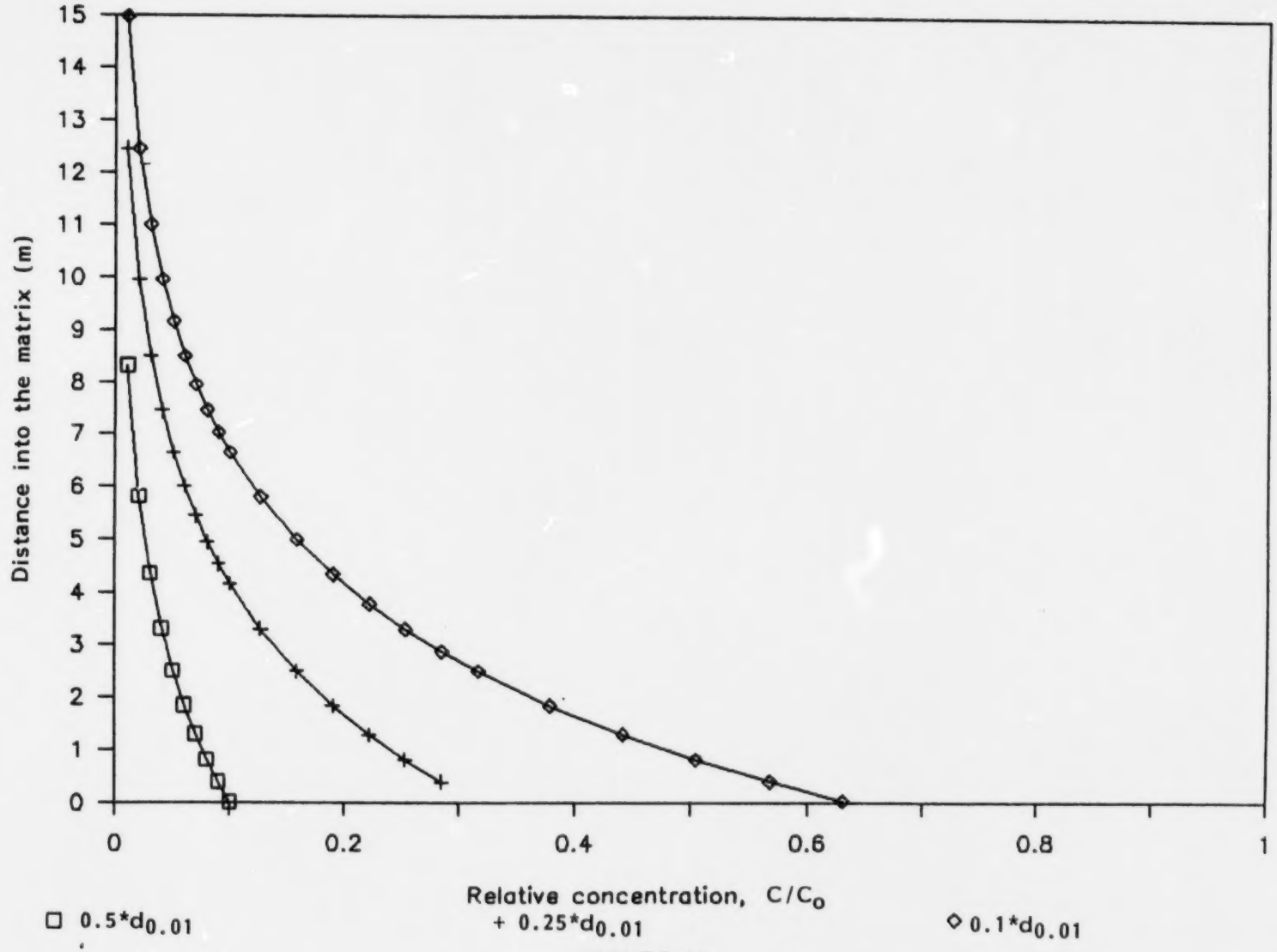


FIGURE 14

STEADY STATE CONCENTRATION PROFILES
2b=10mm: $C^{14}$: D=5.0E-07 $cm^2/s$: $d_{0.01}$=4.47m

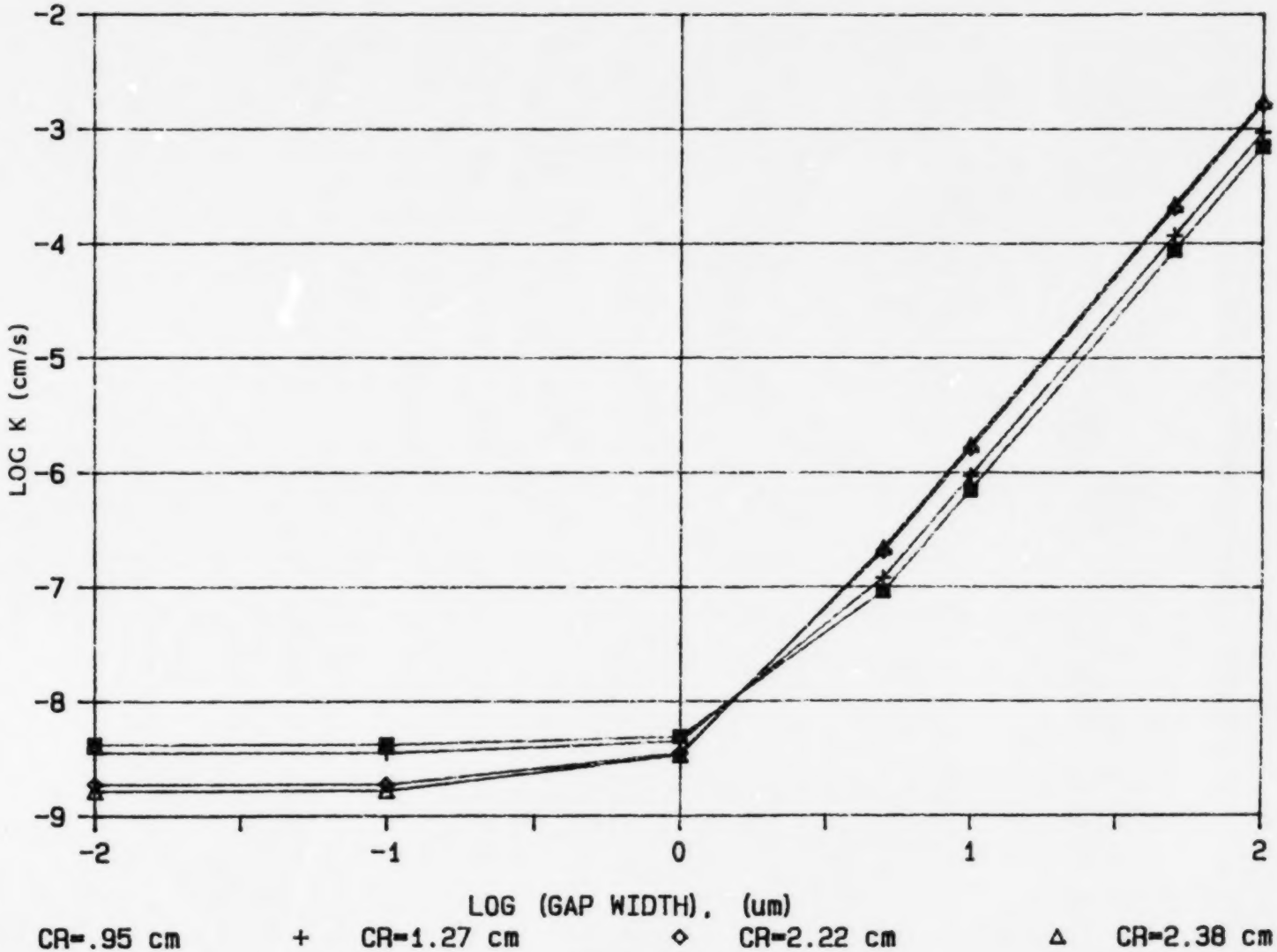


FIGURE 15

SENSITIVITY ANALYSIS OF FLOW IN CLAY/GROUT SAMPLES

K-clay=$6.6 \times 10^{-9}$cm/s: K-grout=$1 \times 10^{-11}$cm/s
SAMPLE RADIUS = 4.76 cm: CR = CORE RADIUS



88-105 176856-RD

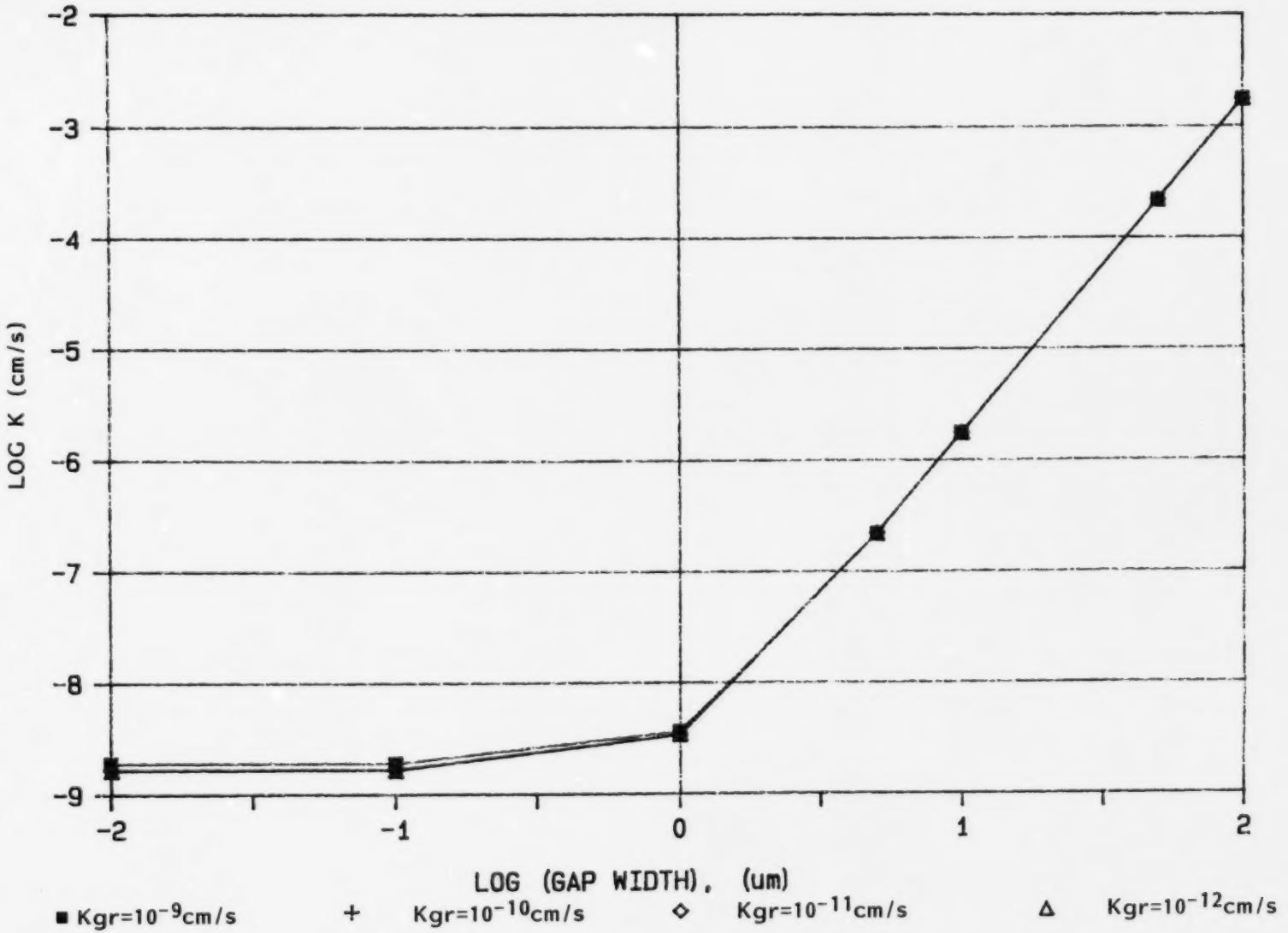


FIGURE 16

SENSITIVITY ANALYSIS OF FLOW IN CLAY/GROUT SAMPLES
K-clay=6.6x10$^{-9}$cm/s: core radius = 2.38 cm: sample radius = 4.76 cm



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APPENDIX

```
************************************************************************
*                                                                      *
*          VARIABLE LIST                                               *
*          A10:  DURATION OF EXPERIMENT IN HOURS                       *
*          CP:  SPECIFIC HEAT OF CONCRETE                              *
*          DIV:  THE NUMBER OF INTERVALS CONTAINED IN A                *
*                SPECIFIC LENGTH                                       *
*          DR:  THE INTERVAL RADIUS ALONG THE PLUG                     *
*          FILNAM:  THE FILE CONTAINING THE RAW DATA                   *
*          FILNMH:  THE FILE CONTAING THE HEATS OF HYDRATION           *
*          FILNMT:  THE FILE CONTAINING THE TEMPERATURES.              *
*          IDX=3: AN INDICATOR TO CHECK IF THE LENGTH                  *
*                 IS WITHIN THE RESTRICTION                            *
*          IDX=2: SENDS AN ERROR MESSAGE IF THE LENGTH IS NOT          *
*                 AN EVEN MULTIPLE OF THE LENGTH INTERVAL              *
*          IDX=1: SENDS AN ERROR MESSAGE IF THE LENGTH INTERVAL        *
*                 IS ZERO                                              *
*          K:  COUNTER                                                 *
*          KC1:  CONDUCTIVITY OF THE CONCRETE                          *
*          KC2:  CONDUCTIVITY OF THE SOIL                              *
*          L:  COUNTER                                                 *
*          R1:  THE RADIUS OF THE CONCRETE PLUG                        *
*          R2:  THE THICKNESS OF THE SOIL AROUND THE PLUG              *
*          RHO1:  DENSITY OF CONCRETE                                  *
*          RHO2:  DENSITY OF THE SOIL                                  *
*          TEM:  ARRAY CONTAINING THE TEMPERATURE RISE                 *
*                AT SPECIFIED TIME INTERVALS                           *
*          TA:  THE AMBIENT TEMPERATURE                                *
*             EVERY HOUR.                                              *
*          TP:  THE PLACING TEMP. OF THE CONCRETE                      *
*          U:  UNIT NUMBER                                             *
*          UN:  THE NUMBER OF UNITS TO BE ANALYSED                     *
*          W:  H. OF H. FOR EVERY HOUR.                                *
*          WCE:  THE WEIGHT OF CEMENT FOR CUBIC METER OF               *
*                CONCRETE.                                             *
*                                                                      *
*                                                                      *
************************************************************************
*
*
*
$LARGE TEM
          DIMENSION W(3000),TEM(361,40)
          REAL KC1,KC2,HYD1,HYD2
          INTEGER UN,U,A10,DIV,DIV1,DIV2,ERFLAG,HR
          CHARACTER*12 FILNMT,FILNMH,FILNAM
          CHARACTER*20 FNAME
          WRITE(*,3070)
          READ(*,1000) FILNMT
          OPEN (8,FILE=FILNMT,STATUS='NEW')
          WRITE(*,3060)
          READ(*,1000) FILNMH
          OPEN(7,FILE=FILNMH)
          READ(7,1000) FILNAM
          READ(7,*) A10, UN
```

```
            WRITE(*,7050)
            READ(*,*) HR
            DO 190 L=1, UN
                  READ(7,*) U
                  WRITE(*,3020)
                  READ(*,*) RHO1,RHO2
                  WRITE(*,3040)
                  READ(*,*) CP1,CP2
                  WRITE(*,3050)
                  READ(*,*) TP
                  WRITE(*,3080)
                  READ(*,*) WCE
                  WRITE(*,3090)
                  READ(*,*) KC1,KC2
                  WRITE(*,4000)
                  READ(*,*) R1,R2
                  WRITE(*,4010)
                  READ(*,*) DR
                  WRITE(*,3095)
                  READ(*,*) TA
                  WRITE(*,1115) R1,RHO1,KC1,TP,CP1,WCE,TA,RHO2,KC2,CP2,
     -                          R2,DR
                  WRITE(*,5500)
                  DO 40 J=1,A10/12
                        READ(7,*) HYD2
                        DO 42 KK=1,48
                              W(48*(J-1)+KK)=HYD1+KK*(HYD2-HYD1)/48.0
 42                     CONTINUE
                        HYD1=HYD2
 40               CONTINUE
 30               CALL DM1HGB(HR,DIV,A10,IDX,R1,R2,DR,KC1,KC2,RHO1,RHO2,
     -                    CP1,CP2,TP,TA,WCE,TEM,W,ERFLAG)
                  IF(ERFLAG .EQ. 1) THEN
                        IF(IDX .EQ. 3) THEN
                           WRITE(*,7000)
                        ELSE
                           IF(IDX .EQ. 2) THEN
                           WRITE(*,7030)
                           ELSE
                           WRITE(*,7040)
                           END IF
                        END IF
                        WRITE(*,7046)
                        WRITE(*,4010)
                        READ(*,*) DX
                     ERFLAG = 0
                     IDX    = 0
                     WRITE(*,5500)
                     GOTO 30
                  ELSE
                  END IF
*****************************************************************
*                                                               *
*           THE FOLLOWING  27 STATEMENTS                        *
*           PRINTS THE RESULTS IN SPECIFIED OUTPUT              *
```

```
*           FILE FILNMT.                                        *
*                                                               *
*****************************************************************
                  WRITE(8,1010) FILNMT
                  WRITE(8,1111) FILNMT
                  WRITE(8,1112) FILNMH,FILNAM,A10/12,UN
                  WRITE(8,1113) U
                  WRITE(8,1115) R1,RHO1,KC1,TP,CP1,WCE,TA,RHO2,KC2,CP2,
     -                          R2,DR
                  WRITE(8,6040)
                  WRITE(8,1040) 0,(TEM(1,I),I=2,DIV+3)
                  DO 50 K=1,A10/HR
                     MM=K*HR
                     WRITE(8,1040) MM,(TEM(K+1,I),I=2,DIV+3)
 50               CONTINUE
                  WRITE(8,8000)
 190        CONTINUE
            STOP
 1000       FORMAT(A12)
 1010       FORMAT(55X,A12,/54X,'**************')
 1111       FORMAT(//5X,'THIS DATA IS STORED UNDER THE FILE NAME ',A12,
     -              6X,'WHERE   15  - AMBIENT TEMPERATURE 15 DEG',
     -             /63X,'       15  - PLACING TEMPERATURE 15 DEG',
     -             /63X,'       10 - WIDTH OF CONCRETE  1.0 M',
     -             /63X,'       TA   - CEMENT TYPE',
     -                        /78X,'TA = TYPE 10        (80 CAL/GR)',
     -                        /78X,'TB = TYPE 10+FA',
     -                        /78X,'TC = TYPE 20        (70 CAL/GR)',
     -                        /78X,'TD = TYPE 40        (55 CAL/GR)',
     -                        /78X,'TE = TYPE 40A       (60 CAL/GR)',
     -                        /78X,'TF = TYPE 40B       (65 CAL/GR)')
 1112       FORMAT(//5X,'HEAT OF HYDRATION DATA USED',9X,A12,
     -              5X,A12,/5X,'NUMBER OF DAYS OF HYDRATION',
     -              ' DATA',4X,I3,/5X,'NUMBER OF UNITS ',
     -              'ANALIZED',14X,I1)
 1113       FORMAT(///5X,'UNIT NUMBER',4X,I2,//5X,'INPUT VALUES ',
     -             'USED IN THE ANALYSIS',/5X,33('-'))
 1115       FORMAT(/5X,'HALF-RADIUS OF PLUG',9X,F4.2,7X,
     -             'DENSITY OF CONC.',10X,F6.1,8X,'CONDUCTIVITY OF CONC.',
     -             4X,F3.1,/5X,'PLACING TEMPERATURE',8X,F4.1,8X,
     -             'SPECIFIC HEAT OF CONC.',5X,F5.1,8X,'WEIGHT OF CEMENT',
     -             7X,F5.1,/5X,'SOIL TEMPERATURE',11X,F4.1,8X,
     -             'DENSITY OF SOIL',11X,F6.1,8X,'CONDUCTIVITY OF SOIL.',
     -             4X,F3.1,/5X,'SPECIFIC HEAT OF SOIL',5X,F5.1,8X,
     -             'SOIL THICKNESS',15X,F4.2,7X,'INTERVAL LENGTH'5X,F6.4)
 1040       FORMAT(1X,I3,2X,20F6.1,4(/6X,20F6.1))
 3020       FORMAT(//1X,'WHAT IS THE DENSITY OF CONCRETE AND SOIL IN ',
     -             'KG PER CUBIC METER?',
     -             /1X,'NOTE:  YOU HAVE TO INCLUDE THE DECIMAL POINT ',
     -             'IN YOUR VALUE',/8X,'USE 2400.0 FOR THIS VALUE')
 3040       FORMAT(//1X,'WHAT IS THE SPECIFIC HEAT OF THE ',
     -             CONCRETE AND SOIL IN J PER KG PER DEGREE CELSIUS?',
     -             /1X,'NOTE:  YOU HAVE TO INCLUDE THE DECIMAL POINT ',
     -             'IN YOUR VALUE',/8X,'USE 921.0 FOR THIS VALUE')
 3050       FORMAT(//1X,'WHAT IS THE PLACING TEMPERATURE OF THE ',
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     -          'CONCRETE IN DEGREE CELSIUS?',
     -           /1X,'NOTE:  YOU HAVE TO INCLUDE THE DECIMAL POINT ',
     -           'IN YOUR VALUE')
 3060     FORMAT(//1X,'WHAT IS THE FILE NAME FOR THE HEAT OF ',
     -           'HYDRATION DATA EG. TYPE10'/)
 3070     FORMAT(//1X,'WHAT IS THE FILE NAME FOR THE TEMPERATURE DATA ',
     -           'EG. 151510TA ?',
     -           /6X,'WHERE   15  - AMBIENT TEMPERATURE 15 DEG',
     -           /6X,'        15  - PLACING TEMPERATURE 15 DEG',
     -           /6X,'        10  - WIDTH OF CONCRETE  1.0 M',
     -           /6X,'        TA   - CEMENT TYPE',
     -                     /21X,'TA = TYPE 10        (80 CAL/GR)',
     -                     /21X,'TB = TYPE 10+FA',
     -                     /21X,'TC = TYPE 20        (70 CAL/GR)',
     -                     /21X,'TD = TYPE 40        (55 CAL/GR)',
     -                     /21X,'TE = TYPE 40A       (60 CAL/GR)',
     -                     /21X,'TF = TYPE 40B       (65 CAL/GR)')
 3080     FORMAT(//1X,'WHAT IS THE WEIGHT OF CEMENT FOR ONE CUBIC ',
     -           'METER OF CONCRETE?',
     -           /1X,'NOTE:  YOU HAVE TO INCLUDE THE DECIMAL POINT ',
     -           'IN YOUR VALUE',/8X,'USE 250.0 FOR THIS VALUE')
 3090     FORMAT(//1X,'INPUT THE CONDUCTIVITY OF THE CONCRETE ',
     -           'AND SOIL IN J/S/M/DEG. C',
     -           /1X,'NOTE:  YOU HAVE TO INCLUDE THE DECIMAL POINT ',
     -           'IN YOUR VALUE',/8X,'USE 2.9 FOR THIS VALUE')
 3095     FORMAT(//1X,'WHAT IS THE SOIL TEMPERATURE IN DEG. C?',
     -           /1X,'NOTE:  YOU HAVE TO INCLUDE THE DECIMAL POINT ',
     -           'IN YOUR VALUE')
 4000     FORMAT(//1X,'INPUT THE HALF-RADIUS OF THE CONCRETE PLUG AND',
     -           /1X,'THE SOIL THICKNESS IN M.',
     -           /1X,'NOTE:  YOU HAVE TO INCLUDE THE DECIMAL POINT ',
     -           'IN YOUR VALUE')
 4010     FORMAT(//1X,'INPUT THE INTERVAL LENGTH IN M',
     -           /1X,'NOTE:  YOU HAVE TO INCLUDE THE DECIMAL POINT ',
     -           'IN YOUR VALUE',
     -          /8X,'USUALLY 0.125 IS USED IF THE SYSTEM IS EITHER ',
     -          /8X,'0.75, 1.0, 1.5, 2.0 OR 3.0 METERS THICK')
 5500     FORMAT(////1X,'***** PLEASE WAIT FOR A FEW SECONDS I AM'
     -                 ' THINKING. ******* ',//6X,'THANK YOU')
 6040     FORMAT(//2X,'HR',2X,'TEMP. OF THE BLOCK IN DEG. C.'
     -          ,'  FROM LEFT TO RIGHT',/2X,'--',2X,47('-'))
 7000     FORMAT(//1X,'**ERROR**  THE SOIL THICKNESS MUST BE A ',
     -           'MULTIPLE OF THE LENGTH INTERVAL'/)
 7030     FORMAT(//1X,'**ERROR**  THE PLUG RADIUS MUST BE A MULTIPLE OF',
     -           ' THE LENGTH INTERVAL'/)
 7040     FORMAT(//1X,'**ERROR**   THE LENGTH INTERVAL CANNOT BE ZERO'/)
 7046     FORMAT(/1X,'RE-ENTER THE LENGTH INTERVAL AGAIN')
 7050     FORMAT(1X,'HOW OFTEN SHOULD THE TEMPERATURE BE OUTPUTTED ',
     -           'IN HOURS, MIN. 2 HR. TO MAX. OF 24 HR.',
     -           /1X,'NOTE:   USE 12 FOR THIS VALUE')
 8000      FORMAT(////1X,'THIS SIMULATION HAS ENDED')
          END
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*                                                                       *
*                                                                       *
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*              S U B R O U T I N E    D I M 1 H G B                *
*                                                                  *
*                                                                  *
*          VARIABLE LIST                                           *
*          ALPHA:  A CONSTANT USED IN EVALUATING THE EQUATION      *
*          A10:  DURATION OF EXPERIMENT IN HOURS                   *
*          CP1:  SPECIFIC HEAT OF CONCRETE                         *
*          CP2:  SPECIFIC HEAT OF SOIL                             *
*          DIFF1,2: VARIABLES USED IN CONVERTING REAL DIVISION     *
*                TO INTEGER                                        *
*          DIV:  THE NUMBER OF INTERVALS CONTAINED IN A            *
*                COMPOSITE CONCRETE/SOIL SYSTEM                    *
*          DR:  THE INTERVAL RADIUS ALONG THE PLUG/SOIL SYSTEM     *
*          I:  COUNTER                                             *
*               ON THE RIGHT                                       *
*          IDX=3: AN INDICATOR TO CHECK IF THE LENGTH              *
*                 IS WITHIN THE RESTRICTION                        *
*          IDX=2: SENDS AN ERROR MESSAGE IF THE LENGTH IS NOT      *
*                 AN EVEN MULTIPLE OF THE LENGTH INTERVAL          *
*          IDX=1:SENDS AN ERROR MESSAGE IF THE LENGTH INTERVAL     *
*                IS ZERO                                           *
*          KC1:  CONDUCTIVITY OF THE CONCRETE                      *
*          KC2:  CONDUCTIVITY OF THE SOIL                          *
*          L:  COUNTER                                             *
*          R1:  THE HALF-RADIUS OF THE CONCRETE PLUG               *
*          R2:  THE THICKNESS OF SOIL AROUND PLUG                  *
*          RHO1:  DENSITY OF CONCRETE                              *
*          RHO2:  DENSITY OF SOIL                                  *
*          T:  HOLDING ARRAY FOR TEMPERATURES EVERY QUARTER OF     *
*              AN HOUR WHICH IS THEN PLACED IN THE TEM ARRAY       *
*          TEM:  TEMPARATURE ARRAY CONTAINING TEMPERATURE RISE     *
*                AT SPECIFIED TIME INTERVALS                       *
*          TA:  THE AMBIENT TEMPERATURE                            *
*              EVERY HOUR.                                         *
*          TP:  THE PLACING TEMP. OF THE CONCRETE                  *
*          W:  H. OF H. FOR EVERY HOUR.                            *
*          WCE:  THE WEIGHT OF CEMENT FOR CUBIC METER OF           *
*                CONCRETE.                                         *
*                                                                  *
*                                                                  *
********************************************************************
*
*
*
      SUBROUTINE DM1HGB(HR,DIV,A10,IDX,R1,R2,DR,KC1,KC2,RHO1,RHO2,
     - CP1,CP2,TP,TA,WCE,TEM,W,ERFLAG)
      DIMENSION TEM(361,40),W(2000),T(100,40)
      REAL KC1,KC2,K1,K2
      INTEGER DIV,DIV1,DIV2,A10,ERFLAG,HR
      IF(DR.EQ.0.0) GO TO 100
      DIV1=INT(R1/DR +.4)
      DIV2=INT(R2/DR +.4)
      DIV=DIV1+DIV2
      DIFF1=ABS(R1-(DIV1*DR))
      IF(DIFF1.GT.0.0001) GO TO 110
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      DIFF2=ABS(R2-(DIV2*DR))
      IF(DIFF2.GT.0.0001) GO TO 120
      DELT=15.0
      BETA1=DELT*60/(RHO1*CP1)
      BETA2=DELT*60/(RHO2*CP2)
      DO 10 II=1,DIV1+2
          T(1,II)=TP
C
C     THE FOLLOWING STATEMENTS INPUTS THE 'TP' INTO THE
C     FINAL MATRIX TEM(  ) FOR THE INITIAL HR=0 VALUE
C
          TEM(1,II)=TP
10    CONTINUE
      DO 15 JJ=DIV1+3,DIV+3
          T(1,JJ)=TA
          TEM(1,JJ)=TA
15    CONTINUE
      K1=KC1
      K2=KC2
      J=DIV1+2
      M=DIV1+3
50    DO 75 K=1,A10/HR
          DO 65 N=1,4*HR-1
              QK=WCE*(W((K-1)*4*HR+N+1)-W((K-1)*4*HR+
     -        N))/(K1*DELT*0.06)
              DO 60 I=2,DIV1+1
                  T(N+1,I)=T(N,I)+BETA1*((K1*(T(N,I+1)-T(N,I))/DR**2)
     -                -(K1*(T(N,I)-T(N,I-1))/DR**2)+((K1/R1)*(T(N,I+1)-
     -                T(N,I-1))/(2*DR))+QK)
60            CONTINUE
              T(N+1,J)=T(N,J)+BETA1*((K2*(T(N,J+1)-T(N,J))/DR**2)
     -        -(K1*(T(N,J)-T(N,J-1))/DR**2)+((K1/R1)*(T(N,J+1)-
     -        T(N,J-1))/(2*DR))+QK)
              T(N+1,M)=T(N,M)+BETA2*((K2*(T(N,M+1)-T(N,M))/DR**2)
     -        -(K1*(T(N,M)-T(N,M-1))/DR**2)+((K2/R2)*(T(N,M+1)-
     -        T(N,M-1))/(2*DR)))
              DO 62 L=DIV1+4,DIV+2
                  T(N+1,L)=T(N,L)+BETA2*((K2*(T(N,L+1)-T(N,L))/DR**2)
     -                -(K2*(T(N,L)-T(N,L-1))/DR**2)+((K2/R2)*(T(N,L+1)-
     -                T(N,L-1))/(2*DR)))
62            CONTINUE
              T(N+1,1)=T(N+1,3)
              T(N+1,DIV+3)=TA
65        CONTINUE
          DO 70 I=2,DIV+3
              TEM(K+1,I)=T(4*HR,I)
              T(1,I)=T(4*HR,I)
70        CONTINUE
              DO 66 N=2,4*HR
                  DO 67 I=2,DIV+2
                      T(N,I)=0.0
67                CONTINUE
66            CONTINUE
75    CONTINUE
      RETURN
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100   IDX    = 1
      ERFLAG = 1
      RETURN
110   IDX    = 2
      ERFLAG = 1
      RETURN
120   IDX    = 3
      ERFLAG = 1
      RETURN
      END
```